Απελευθέρωση Αγορών Ηλεκτρικής Ενέργειας:

Κίνητρα για Επενδύσεις στο Δίκτυο Μεταφοράς στα πλαίσια της Αναδιοργάνωσης των Αγορών Ηλεκτρισμού.

Αφιερωμένο στους αγαπημένους μου γονείς,

Σωτήρη και Λεμονιά.

Πρόλογος

Η παρούσα εργασία ασχολείται με ένα θέμα που είναι ευρέως διαδεδομένο στην αρθρογραφία, αυτό της εξασφάλισης κινήτρων για επενδύσεις στο δίκτυο μεταφοράς ηλεκτρικής ενέργειας. Αρχικά, παρουσιάζουμε τις κυρίαρχες αντιλήψεις που επικρατούν όσων αφορά την αναδιοργάνωση των αγορών ηλεκτρικής ενέργειας, καταλήγοντας στο συμπέρασμα ότι ο διαχωρισμός της παραγωγής, της μεταφοράς και της διανομής του ηλεκτρισμού αντιμετωπίζει σοβαρές δυσκολίες στην εφαρμογή σωστών μηχανισμών παροχής κινήτρων για νέες επενδύσεις στο δίκτυο. Στο δεύτερο μέρος της εργασίας, και με τη βοήθεια ενός απλού ολιγοπωλιακού μοντέλου, υπολογίζουμε την αξία που έχει η προσθήκη μιας γραμμής που συνδέει τους δύο παραγωγούς – τόσο σε κοινωνικό όσο και σε ιδιωτικό επίπεδο. Με την ανάλυση που ακολουθεί, επιβεβαιώνεται ότι μία αλλαγή στη μορφή του δικτύου, ενώ είναι ευεργετική σε έκτακτες περιπτώσεις, μπορεί εντούτοις να προκαλέσει αρνητικά αποτελέσματα όταν το δίκτυο λειτουργεί κανονικά. Αυτές οι αρνητικές επιπτώσεις οφείλονται στους περιορισμούς στη ροή της ενέργειας, που επιβάλλονται από τους νόμους του Kirchoff, και ισχύουν ακόμη και σε περιπτώσεις που η χωρητικότητα της γραμμής είναι αρκετά μεγάλη. Επιβεβαιώνοντας το γεγονός ότι μία επένδυση μπορεί να είναι κοινωνικά αναποτελεσματική και ταυτόχρονα επωφελής για αυτόν που την κάνει ευθυγραμμιζόμαστε με την κυρίαρχη άποψη στην αρθρογραφία που συνεχίζει να αναζητά τους μηχανισμούς που θα παρέχουν σωστά κίνητρα για επενδύσεις στο δίκτυο μεταφοράς. Το συγκεκριμένο θέμα αναλύεται διεξοδικά στο τελευταίο μέρος αυτής της εργασίας, όπου βελτιώνουμε και επεκτείνουμε το μοντέλο που προτάθηκε από τους Bushnell και Stoft (1996). Ο μηχανισμός που παρουσιάστηκε στο συγκεκριμένο άρθρο αποκλείει τις «κακές» επενδύσεις, αλλά παράλληλα αποθαρρύνει ένα σημαντικό μέρος των «καλών» επενδύσεων. Εμείς κινούμαστε ένα βήμα παρακάτω και αποδεικνύουμε ότι αν επιβάλλουμε έναν εφάπαξ φόρο στους κατόχους του δικτύου, μπορούμε να επιδοτήσουμε τους επίδοξους επενδύτες, εξασφαλίζοντας ταυτόχρονα ότι καμία επένδυση με κοινωνική αξία μεγαλύτερη του κόστους της δεν θα αποκλειστεί. Τέλος, αποδεικνύομε ότι ο παραπάνω μηχανισμός ισχύει ακόμη κι όταν υπάρχει αβεβαιότητα για την προσφορά και τη ζήτηση.

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Κατ' αρχήν, θα ήθελα να ευχαριστήσω τον επιβλέποντα καθηγητή μου, κ. Χρήστο Κωνσταντάτο, για την πολύτιμη βοήθειά του σε κάθε στάδιο της εκπόνησης αυτής της εργασίας και γιατί μου έδωσε την ευκαιρία να ασχοληθώ με το συγκεκριμένο θέμα, που άπτεται στα επιστημονικά μου ενδιαφέροντα. Ήταν χαρά και τιμή μου να συνεργαστώ μαζί του, καθώς η συνεργασία μας ήταν πολύ εποικοδομητική για μένα και οι συμβουλές του ήταν καθοριστικής σημασίας για την ολοκλήρωση αυτής της εργασίας.

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Τέλος, οφείλω ένα πολύ μεγάλο ευχαριστώ στους γονείς μου, Σωτήρη και Λεμονιά για την ανεκτίμητη και αδιάκοπη υποστήριξή τους τόσο σε ψυχολογικό όσο και υλικό επίπεδο. Χωρίς την δική τους συμπαράσταση δε θα μπορούσα να ολοκληρώσω αυτήν την εργασία και τις σπουδές μου, γενικότερα.

Liberalization of Electricity Markets:

Network Investments Incentives
In the Deregulated Electricity Markets

"Success:
It is not the position you stand,
but the direction in which you look."

Dedicated to my beloved parents,
Sotiris, and Lemonia.

Abstract

This work contributes to the literature on merchant incentives for electricity network expansion. We first present the main approaches to the organization of a deregulated electricity market. We conclude—along with the existing literature—that the vertical separation of generation, transmission and distribution creates substantial difficulties in finding and implementing a correct incentives mechanism for new investments in the network. In the second part of this work we use a simple oligopoly model in order to investigate the value—both social and private—of adding a line connecting two generators. While useful under adverse conditions, such network modification may have negative impact under normal circumstances. This impact is due to flow constraints imposed by Kirchoff's law, and does not disappear even if the constructed line is large. We show cases where the network expansion may be socially damaging while privately profitable. By confirming the presence of negative externalities in network expansions, our conclusions are in line with the literature calling for a correct investment incentives mechanism. This issue is taken up in our last chapter where we improve the investment incentives mechanism proposed in Bushnell and Stoft (1996). The mechanism proposed in that work excludes "bad" investments but cannot guarantee that all "good" investments will be undertaken. By adding a subsidy financed by a lump sum tax on incumbent network owners, our mechanism guarantees that no investment with social value greater than its cost will be ignored. We also show that this mechanism is robust under stochastic demand conditions.

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Contexts

Liberalization of electricity markets: The case of a transmission grid expansion.

Introduction

Electricity supply has traditionally been characterized by vertically integrated monopolies subject to public regulation: generation, transmission and distribution of electricity was considered as a bundled product, typically at the responsibility of a single regulated or nationalised firm. In the last decades, however, many countries have been directed to restructuring of their electricity sectors, in order to create unregulated competitive generation-services markets with many competing generation suppliers and free entry. The procedure of electricity sector reorganization started from the US market with the Order 1992 and has been followed by other countries that have restructured or are in the process of restructuring their electricity sectors, Greece being included in the second category. As a result many ideas and different, often controversial, practices have been developed in recent years, when the liberalization of the electricity markets was becoming reality in many countries all over the world.

The main difficulty in adopting a common standard for all electric power markets streams from the special characteristics of the electric power, and therefore each country adjusts its electricity regime according to its individual institutions and legislation frameworks. Two dominant models of electricity markets organization have been developed: the ISO model, mainly based on merchant transmission investments, and the Transco model, based on a regulated firm that not only operates but also owns the electricity transmission network. While both these models focus on the rules under which the electricity system will operate, the main problem the electricity sector has to solve is that of network investments. The possibility of under-investment or no investment at all in the network remains present under both systems and many models have been proposed in order to avoid this contingency. Hence, the research has been turned to the direction of providing adequate incentives for market participants or the regulated system operator to invest in the network in an efficient way and eliminating the negative externalities such investments may have.

This work handles with the transmission investment issue examining its impacts on the market participants, taking also into account the capacity constraints imposed by the existing network lines. We demonstrate the negative externalities created by such an investment due to the implications of Kirchoff's laws, and seek for alternatives in providing adequate transmission investment incentives under the merchant model.

In what follows, chapter 1 demonstrates the special characteristics of the electricity, which differentiate it from any other commodity and have significant impacts in the adaptation of a common standard in the liberalization of electricity markets. Chapter 2 summarizes the literature over the restructuring of the electricity market by presenting the two dominant approaches of the electric power organization, the ISO model and the Transco model. That part of the work also points out the different incentive mechanisms related to each model.

Chapter 3, which contains the major part of the analysis, presents a 3-node model in order to examine the potential negative externalities a lumpy transmission investment may have, focusing on its impact on the social welfare and the producers' surplus. Our research allows to estimate the value of a new line added to an existing network, in welfare terms and recognizes the potential negative externalities this new line may have on market participants. Chapter 4 illustrates the Bushnell and Stoft (1996) *"Electric Grid Investment under a Contract Network Regime"* (B&S) and extends its implications by proposing a mechanism that not only avoids detrimental investments - as in B&S, but also motivates the investors to invest on the network in a sufficient way. Moreover, it extends the scope of the proposed investment incentive mechanism by adapting it to cases of demand uncertainty. Finally, section 5 contains the concluding remarks of this work.

Chapter 1: Description of electricity market peculiarities

Electricity, undoubtedly, has been a very important invention, that spotted positively the evolution of human life. Its discovery and development has created new opportunities in the improvement of living conditions, since it is mainly responsible for the revolution in the productivity sector, in transports, in (tele)communications, in the technological and scientific growth etc. Electric power is like no other commodity and its unique characteristics make the organization of the electricity markets a very complex matter.

Before discussing the characteristics of electric power, let us give first a simple definition of electricity:

Definition 1: *Electricity is the simultaneous and in one direction movement of electrons (negative electric charge) caused by the electrical potential difference between two points of an electric circuit*.

1.1. The special characteristics of electricity

Below we try to summarize the most important characteristics of electricity that differentiate it from the other commodities and have also significant impacts on the organization of electricity markets:

Differentiation: Electricity, even more than almost every other commodity traded, is remarkably homogenous (all electrons are identical), but, like other commodities, must be distinguished by time and place: a MWh at 5:30 pm on a winter weekday is very different (and has on occasion been as 100 times as valuable) as a MWh at 3 am on the following morning. Likewise, electric power produced by a generator in the area A may not be substitutable with the electric power produced by a similar generator in area B, during periods when the transmission network is congested.

Impossibility of storage: The major difference between electricity and other commodities is that the former is in many cases impossible to store. Although, water in storage hydro systems can provide a good proxy for storage, this technique is not always applicable and, when it is, it is extremely costly. The above statement leads to the need that demand must be at every time equal to supply.

Instantaneous balancing of demand and supply: The electricity markets require instantaneous and continuous balancing of their demand and supply resources. In other words, supply must be equated to demand second by second and failure to do so, threatens the stability of the network. In turn network instability may result in disruptions not only affecting the market participants who caused the imbalance, but the system as a whole. Thus a slight deviation between demand and supply may lead to the collapse of a transmission line, or, worse, to a general black out. The effort to maintain continuous electrical equilibrium is further challenged by the fact that almost all end-consumers do not have the metering technology to observe or the economic incentives to respond to real-time prices. This implies that little or none of the supply/demand balancing can be done through the demand side. Thus, the **reliability problem** in electricity markets has two dimensions: in the short-term, *supply security* requires that existing capacity is ready to meet the actual load; *supply adequacy*, instead, refers to the long-run performance attributes of the system in attracting investments in generation, transmission, distribution, metering, and control capacity so as to minimize the costs of power supplies.

Tight quality constraints: Another special characteristic that differentiate the electricity markets from all the other markets is the ancillary services, which generator companies are obliged to provide. The electric power system, as a whole, must not only supply consumers with adequate energy, but also has to maintain the quality of electricity in good standards. Electricity quality consists of the following parameters: frequency, voltage standards, and phase angle standards; all these parameters must be maintained within tight limits at any time[1]. The same effect has also variation in the voltage levels[2], i.e. an important voltage fall or increase may cause electric equipment failures or even outages of a transmission line. These requirements impose numerous

[1] For instance, the frequency of the electric current must be remained at the determined level of 50Hz in Europe (or 60Hz in America), otherwise all electric devices constructed to operate on these levels, may be destroyed.
[2] In Europe the voltage level in the low voltage network is 230V

constraints (voltage constraints, thermal constraints etc.) on the electric network, and combined with the capacity constraints of the lines make the organization of electricity markets quite problematic.

1.2. The Loop Flow Problem

If the combination of technical requirements specific to the electric power system with the economic terms of the liberalization of electricity sector is not an easy task, the most disturbing characteristic of electricity, namely the *loop flow problem*, has yet to be mentioned.

As other network commodities, like gas, trains *etc*., the electric power flows through a complicated network of lines and nodes. However, electricity significantly differs from other network commodities in the way it flows through its network. Actually, the movement of electrons as determined by *Ohm's and Kirchoff's' laws,* follows the path of least resistance, causing power to move across many parallel lines in often circuitous routes. One of the most important economic implications of this prevalence of loop flow is that the power transmission highway is very unlike other highways, and analogies with railroads or pipelines can be quite misleading. Despite its economic implications, the loop-flow problem is little understood by the layman, for this reason it will be presented below.

Proposition 1: *The electron's movement follows the path of least resistance.*[3]

[3] *Proof:* We first demonstrate the Ohm's law. According to it, the current I that pass over a line with resistance R is given by the following equation: $I = \frac{V}{R}$ (1), where V stands for the voltage level. Taking into account that $R = \rho \frac{l}{s}$ the equation (1) becomes $I = \frac{Vs}{\rho l}$ (1.1a), where *s* is the cross-section of the line, *ρ* a parameter called special resistance and l stands for the length of the line. From equation (1a) we conclude that considering *V* and *s* as constants, the current (and the electric power, accordingly) reversively depends on the length and resistance of the line. So, the statement has been proven, if we clarify that the current is a measure for the electrons' movement. •

Below we will try to illustrate the implications of Kirchoff's laws in simple words considering the following 3-node example. Assume the following topology: there are three different areas, each represented on a different node in Figure 1.1. In each area there are both electric power generators and consumers, which implies that power flows in every possible direction in the network. In Figure 1 q_{ij} is the power that electric power generators and consumers, which implies that power flows in every possible direction in the network.

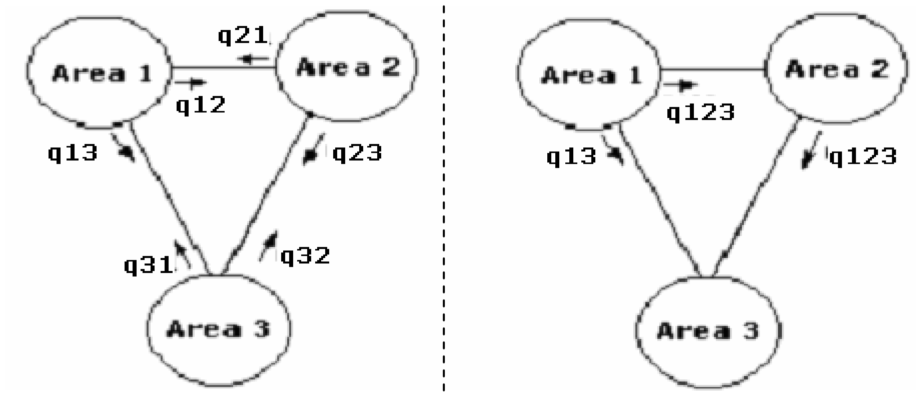


Figure 1.1

In Figure 1 q_{ij} is the power that flows from area *i* to area $j(i, j = 1, 2, 3)$. The electric power that flows in each direction must satisfy the following system of equations:

$$
\begin{aligned}
q_1 &= q_{12} + q_{13} \\
q_2 &= q_{21} + q_{23} \\
q_3 &= q_{31} + q_{32} \\
q_{12} + q_{21} &= 0 \\
q_{13} + q_{31} &= 0 \\
q_{21} + q_{12} &= 0
\end{aligned}
\tag{1.2}
$$

where q_i, *i=1, 2, 3* is the electric power exported or imported in area *i*. When *q* takes positive values then the specific area exports electric power, while negative values of *q* imply that the specific area imports electric power.

Now, suppose that areas 1 and 2 are the generating regions and area 3 is the load region (consumption). Also, consider that all three lines are *identical i.e.* they all have the same length and the same resistance. The flow of electric power follows Kirchoff's laws. If there is no power generated at node 2, then the only energy supplier at bus 3 is the generator at node 1. Since the path $1 \rightarrow 2 \rightarrow 3$ is twice as long as the path $1 \rightarrow 3$ and the lines are identical, it has twice as much resistance. According to the above laws the power q_{13} must be twice the power that flows in the path $1 \rightarrow 2 \rightarrow 3$ (q_{123}).

Chapter 2: Literature Review

Within the past decade[4], the electric power industries have been restructured from mainly regulated by vertically integrated monopolies (where the generation and the transmission sectors were jointly planned and operated) to deregulated sectors, where generation and transmission are planned and operated by different entities. Under the integrated monopoly structure planning and investment in generation and transmission, as well as operating procedures, were, at least in theory, closely coordinated through an integrated resource planning (IRP) process. This process accounted for the complementarity and substitutability between the available resources in meeting reliability and economic objectives. The vertical separation of the generation and transmission sectors has resulted in a new operation and planning paradigm where IRP is no longer a viable alternative. Planning and investment in the privately owned generation sector is driven by economic considerations in response to market prices and incentives. The transmission system, on the other hand, is operated by independent transmission organizations that may or may not own the transmission assets, they are using. Whether the transmission system is owned by the system operator as in the UK, or by separate owners, as in some parts of the US, its operator plays a key role in assessing the needs for transmission investments from reliability and economic perspectives. With few exceptions, the primary drivers for transmission upgrades and expansions are reliability considerations and interconnection of new generation facilities. However, because the operating and investment decisions by generation companies are market driven, valuation of transmission expansion projects must also anticipate the impact of such investments on market prices and demand response. Such economic assessments must be carefully scrutinized since market prices are influenced by a variety of factors including the ownership structure of the generation sector, the network topology, the distribution and elasticity of demand, uncertainties in demand, as well as generation and network contingencies.

[4] E. Sauma – S. Oren (2006), “Proactive planning and valuation of transmission investments in restructured electricity markets”.

2.1. Different Approaches for Electricity Markets Organization

In literature, as well as in practice, many different approaches about the electricity sector organization have been developed. So, in order to obtain a complete idea of how electricity markets are being restructured, it is quite instructive to set out some examples derived from different practices. Starting, we follow the whole deregulation process of the U.S. electricity industry. Below we point out the two dominant approaches of electricity market organization, *i.e.* the Independent System Operator (ISO approach) and the Transmission Company (Transco approach).

The US electricity market organization and development has been analytically demonstrated in Joskow (2005). According to this paper, the US electricity industry was characterized by an unusually large number of private vertically integrated utilities of widely varying sizes that own and control generation, transmission, and distribution facilities in or near their distribution franchise areas. Many of these vertically integrated utilities composed the control area operators (about 140 separate US control areas in 1995) that were - and in many cases still are - responsible for operating portions of one of the three synchronized AC networks in the US, subject to rules established by the regional reliability councils and a variety of bilateral and multilateral operating agreements. To meet their obligations to their franchise customers in the pre-liberalization regime, vertically integrated utilities acquired and operated generation (*G*), transmission (*T*) and distribution assets (*D*). State regulatory agencies set the prices at which electricity was sold to retail consumers, evaluated the reasonableness of the costs incurred by the utilities they regulated. Regulated (bundled) retail prices were based on the utility's overall (*G*+*T*+*D*) accounting cost of service, where a utility's cost of service or ''revenue requirement'' was defined as:

$$R = OC_D + OC_G + (r+d)[K_D + K_G - \sum d_{-t}] + T \qquad (2.1)$$

where OC_i is the operating costs of distribution, generation and transmission facilities, K_i is the original cost of capital investments in distribution, generation and transmission facilities, r is the allowed rate of return on capital investment, *d* is the annual depreciation rate, $\sum d_{-t}$ is the accumulated historical depreciation of distribution, generation and transmission facilities based on original cost, and *T* is income and property taxes.

In other words, retail prices ‘‘bundled’’ generation, transmission and distribution costs together, though concepts of bundling and unbundling evolved long after these pricing procedures were defined. The aggregate revenue requirement *R* was then allocated to various customer classes (residential, commercial, industrial) based on the voltage level at which they took power, load factors, peak demand and other considerations, to come up with a set of price schedules or ‘‘tariffs’’ that specified the bundled retail price for electricity service. No separate price for transmission service was either visible or calculated by state regulators. Moreover, the Federal Energy Regulatory Commission (FERC) had no authority to require utilities to provide ‘‘unbundled’’ transmission service to third parties seeking to use their transmission networks in order to buy power from a remote generation source or to sell power to a remote load. By the 1990s, most utilities did ‘‘voluntarily’’ provide some unbundled transmission service to other neighbouring vertically integrated utilities as well as to municipal and cooperative distribution companies, which were seeking power supply alternatives to the vertically integrated utility within whose network they were embedded.

After 1992, however, when the Energy Policy Act was established, the road of restructuring and liberalization of the electricity sector had opened. Many orders and legislation frameworks (Order 888/889, Order 2000) followed to conclude to the Standard Market Design (SMD) proposal, proposed in 2002 by FERC. The SMD proposal applies to all transmission-owning utilities over which FERC has jurisdiction. In order to better understand the SMD proposal, and the ISO approach that SMD imposes, we will analyse below the operation of the PJM system (Pennsylvania, New Jersey, and Maryland Interconnection) where SMD implementation is most advanced.

The following five points depict the PJM system:

1. PJM is a not-for-profit independent system operator and has been qualified as an ISO by FERC pursuant to Order 2000. PJM is not a market participant, does not own *G, T*, or *D* assets and is not engaged

in wholesale or retail marketing. PJM is responsible for system operating reliability and for applying reliability rules and criteria developed by regional reliability councils

2. PJM operates (voluntary) day-ahead and real-time (adjustment or balancing) bid-based markets for energy and ancillary services. Market participants submit bids and offers to the day-ahead and real-time markets. Locational Marginal Prices (LMP) that balance supply and demand at each location on the network and the allocation of scarce transmission capacity are performed together using a least cost bid-based security constrained dispatch (state estimator) model that incorporates the physical topology of the network and reliability constraints. The LMPs reflect equilibrium marginal energy costs, marginal losses (in New York and New England and soon in PJM), and the marginal cost of congestion at each location.
3. Congestion is priced based on the difference in LMPs between the designated delivery and receipt points of generation supplies chosen by a transmission service customer.
4. Participation in day-ahead and real-time markets is voluntary in the sense that generators, loads, and marketing intermediaries may submit their own day-ahead schedules for energy and ancillary services to the ISO and can use bilateral arrangements to stay in balance in real time. However, bilateral schedules are still liable for congestion and loss charges and any residual imbalances are settled at the real-time prices determined in PJM's spot market.
5. Self-supply of ancillary services is permitted, but the associated generators or demand response must be identified and under the control of PJM.

The above remarks provide an intuition of how the ISO model is applied in practise. The PJM system represents the structure of a centralized ISO that has been used in many places, i.e. Argentina, Australia, and Texas. Moreover, in the Mexican electricity market approach, the ISO is supposed to operate a market for large consumers, while the existing state utility to retain its vertical integration and provide services exclusively for small consumers. However, all these independent entities own no transmission assets, have no linemen or helicopters to maintain transmission lines and respond to outages, and are not directly responsible for the costs of operating, investing in, or the ultimate performance of the transmission networks they ‘‘manage.’’

Wilson (2002) among others presents another possible structure for a system operator, namely an integrated company that combines ownership of the transmission network with the system operator. According to Wilson, there are four markets that characterize the electricity market: the forward transmission market, the spot energy market, the forward energy market (or market of bilateral contracts), and the forward market for reserves. The Transmission Company (Transco) proposed by Wilson operates this four markets and also is in charge of the transmission network. The Transco approach is similar to a centralized ISO which not only controls the network dispatch, but also owns the transmission grid. The Transco is penalized when increasing the congestion costs and the regulator forces it to operate effectively. Such a market organization has been employed in the British and Wales electricity market, in Spain, and Scandinavia.

The major difference between the two models is that the Transco is a profit-making entity, as opposed to an ISO, and is responsible for maintaining and expanding the transmission grid. On the other hand, in the ISO model the transmission investments should be carried out by the agents of the electricity markets on a merchant basis. Joskow and Tirole (2002) favours the Transco approach because the separation between transmission and system operation, imposed by the ISO model, may lead to high coordination costs. In practice, the decision between the two options is based on institutional conditions. As Hogan (1999) says Ni the U.S. market is impossible to apply the Transco model because the property structure of the transmission network is such that it would result in many small regional Transcos with compatibility problems. In each case, however, it seems that transmission and system operation must be separated from generation in order to avoid conflicts of interest (Hunt 2002).

2.1.1. The Greek Electric Power Market Organization

In Greece, the restructuring procedure or electricity sector has begun in 1999 with the Order 2773/99. Up to 1999 the greek Public Power Corporation (PPC) was the dominant authority that had electric power generation, transmission and distribution under its exclusive control. The new Order constitutes the basic legal background and provides the framework for the liberalization of Greek electricity sector. The Greek electric power system is based on the ISO model. Two entities have been created: the Regulatory Authority of Energy (RAE) as well as Hellenic Transmission System Operator (HTSO). RAE is an independent authority that manages, suggests and promotes the existence of equal opportunities and fair competition and gives the operation license to producers/providers, related to the electricity market. Its role in the electricity market is the same as this of the capital market commission in the exchange market.

HTSO is a S.A. company, the 51% of which belonging to the Public Sector, and the 49% belonging to the electricity production companies existing in Greece. This means that PPC today owns this 49% but its share will be decreasing giving the opportunity to new producers may appear to increase their share. HTSO S.A. has a double role in the new liberalization era of electric power market[5]:

- The first role of HTSO is to guarantees the existence of a balance between production and consumption and the electric energy to be provided in a reliable, safe and in terms of quality acceptable way.
- The second role of HTSO is to settle the market, in other words to act like an energy stock market that arranges on a daily basis who owes to whom. HTSO does not provide electric energy and whatever basic exchanging relations exist they are bilateral ones between producers/providers and their customers.

Moreover the system operator has a number of responsibilities:

- First the produced, transmitted and consumed energy has to be measured accurately and in a way that is indisputable by market anticipants. First

[5] See at the official site of the HTSO (www.desmhe.gr)

procedure of the Operator's responsibility is the existence of a metering system being officially certified.

- Second, the system operator is in responsible for the operation of, what consists the heart of the electric power system, the *Dispatching Center*. It is well known that electric energy is an idiomorphic commercial good that can not be stored, and thus at any time the production will have to be equal to the consumption. It is the Dispatching Center that has to settle the schedules of which station is going to produce in what quantity. The Dispatching Center dispatches each station in such a way so that the quality characteristics (currency, frequency) are maintained, the operational cost is the minimum one and the bilateral commercial relations between consumer-providers are respected.
- Third, it is responsible for the reliability of the electric power system.In order to maintain this reliability the quality characteristics of the delivered electric energy to the consumers, the Operator needs specific *auxiliary services* that are obtained through transparent procedures by market producers.
- Fourth, the HTSO controls and administers the settlement of the electrity market. The settlement is a procedure related to the purchase of electric energy. The Greek electricity market is based upon a system of bilateral commercial relations between consumer and producer. The Operator does not interfere in these bilateral agreements, which are under the absolute authority of the contracting parties. However during the daily operation and for several reasons a provider's production is not absolutely equal to a client's consumption. This deviation is been calculated and invoiced by the Operator who dictates to any incomprehensive producer the amount he is going to pay through the Operator to an other producer. This procedure is called clearing of the market and is been arranged in such a way as to encourage the economic operation of the System.
- Fifth, the Operator is responsible for the maintenance of the system and its further development in order to accept new producers and new customers. This maintenance will be implemented by PPC (as the owner of the grid) while the expansions will be charged according to very specific rules being included in the norms of interaction governing the market. -Finally, one of Operator's duties is the support and further development of the market and

the improvement of the interested parties. The Operator makes short, mid and long term forecasts for the needs of the system, publishes estimations, and finally proposes improvements to the market rules and to the operation of the system.

HTSO's aim is to achieve a reliable and impartial operation of the Hellenic Transmission System Operation as well as of the market that depends on it, so that the new producers, the selected customers and all consumers to rely on a electric power system, which should be characterized by transparency and impartiality. However, impartiality and transparency may be jeopardised as long as there is a firm that plays a dominant role in the system operator's structure. A test of the efficiency of the new electricity system will be the extend of new entry and the reduction in market concentration.

2.2. Transmission Network Investments.

As it has been illustrated above, the most important problem in the electricity markets liberalization is the definition of the regime that will govern the transmission network. The question that still remains open is in what ways the transmission investments could be motivated and how the dangers of underinvestment-both in the short run and the long run-in the transmission grid could be eliminated. Many aspects have been developed in the literature of the incentives in transmission expansion. Generally, this discussion has been centred in the two approaches that have been already reported, each one having its own incentives providing mechanisms.

2.2.1. Regulatory incentives mechanisms.

At one end of the spectrum there is the approach of the *regulated investments*. Under the regime of a regulated firm owning the transmission network (Transco model) things are quite complex. This approach, quite popular in the literature, creates the appropriate incentive regulatory mechanism for a Transco to provide incentives to the regulated firm to make efficient investment decisions. It also permits the regulated firm to earn enough revenues to cover capital and operating costs in an imperfect information environment about cost and demand functions.

Many works, among them Leautier (2000), propose mechanisms that relate Transco's performance to a measure of welfare loss due to its activities. The regulator offers a menu of contracts that induces the firm to invest on the transmission network in a sufficient way, while still permitting it to recover its costs. Under this mechanism, the firm is responsible for the costs of congestion it creates and the investment needed to relieve it. Leautier (2000) shows that a marginal increase in transmission capacity has two effects: a direct effect, consisting of the substitution of cheap to expensive power, and an indirect effect reflecting the results of an expansion on other transmission lines. The latter represents the negative externalities created by a lumpy expansion in electricity networks[6]. Leautier (2000) defines the cost of congestion as the difference between the price actually paid to generators and the price that would have been paid absent congestion. In such a case, Transco has an incentive to minimize congestion, while a separate mechanism provides incentives to invest in the optimal amount of transmission investment.

Vogelsang (2001) proposes a *price structure regulation* based on the two-part tariff model. It states that Transco is a profit-maximizing monopolist that makes investments and pricing decisions subject to regulation of its two-part tariff. Vogelsang's mechanism works as follows: in times of excess capacity, the variable charge of the two-part tariff decreases, causing an increase in consumption. The fixed charge, in turn, increases, so that total income increases despite the reduction of the variable charge. As a consequence, the Transco is not induced to invest excessively in capacity expansion and net profits grow since costs do not go up. On the contrary, when there is congestion in capacity, the variable charge will be a pure congestion charge and, if congestion charges are in the margin greater than the marginal costs of expanding capacity, the Transco will have incentives to

[6] The construction of a new line may create congestion to an already existed line hurting finally the producers or the consumers that benefit from it.

invest in new capacity. This regulatory mechanism seems to be superior (in welfare terms) to a linear price cap mechanism.

Another incentive regulatory mechanism applied in Transco models is that of a *fixed price* regulatory contract or a *price cap* regulatory mechanism. Under price cap regulation the regulator sets an initial price p_0. This price is then adjusted from one year to the next for changes in inflation (*RPI*) and a target efficiency change factor (or productivity change factor, *X*). Accordingly, the price in period 1 is given by:

$$p_1 = p_0(1 + RPI - X) \tag{2.2}$$

Because prices are fixed, the firm keeps all the benefits created by any cost reduction. In other words this mechanism provides the regulated firm incentives to reduce its costs. However, as Joskow argues any incentive regulation mechanism that provides incentives only for cost reduction also creates incentives to inefficiently reduce service quality, when service quality and costs are positively related to one another, as is the case of the electricity sector.

The regulatory mechanisms are not limited to only providing incentives for network investments and cost reduction to the regulated firms. Another quite important aspect is the *service quality incentives*[7]. Since, price cap mechanisms may deteriorate the quality of the services provided by the operator, these *fixed price structures* are usually accompanied by a set of performance standards and associated penalties and rewards for falling above or below these standards. Such an incentive mechanism has been applied in U.K. electricity sector, in order to retain the electric power system reliability at acceptable levels. That regulatory mechanism focuses on the reliability of the transmission network as measured by the quantity of “unsupplied energy” resulting from transmission grid outages. So, the British Transco (National Grid Company or NGC) is assessed penalties or receives rewards when outages fall outside of a “dead-band” of $\pm 5\%$ defined by the distribution of historical outage experience (and with potential adjustments for

[7] Recall that service quality should be kept at high levels in order to guarantee the optimal operation of the electric power system as a whole.

extreme weather events). Similar mechanisms are also used by certain US states as well as in other countries that have liberalized their electricity sectors (e.g. New Zealand, Netherlands, and Argentina).

In concluding the presentation of regulatory mechanisms for transmission expansion, we need to emphasize the implementation hurdles they face. For example, Joskow and Tirole (2003) recognizes that its scheme might not work when the Transco is vertically integrated with generation so that the integrated company can manipulate bids in the energy market. This is particularly alarming for the Greek system operator, since the Public Power Corporation owns to date a dominant share of its assets.

2.2.2. Merchant incentives mechanisms

At the other end of the spectrum we have *merchant transmission investments*, which can be simply defined as "market participants making transmission investments in response to market incentives"[8]. The merchant transmission investments approach is used in the ISO models, where the system operator does not own transmission network assets, and transmission investments are, therefore left to market participants. Since these investments are voluntary, it is crucial to establish a mechanism able to induce all the efficient network modifications, while deterring the insufficient ones. However, the determination of proper incentives for market participants to undertake efficient transmission investments is a quite difficult matter.

The merchant incentives mechanism must rely on competition, free entry in the electricity generation market, decentralized property-rights-based institutions and market-based pricing of transmission services in order to govern transmission investment. In return for investment in additional transmission capacity, merchant investors receive property rights that allow them to collect congestion revenues equal to the difference in nodal energy prices associated with the incremental point-to-point transmission capacity their investments create. The value of these rights on congestion revenues represents the revenues merchant investors receive in order to cover the

[8] See Hogan (2003).

capital and operating costs of their investments, thus providing the financial incentives that guide ‘market based’ transmission investment.

In literature, there are two general approaches to allocating scarce transmission capacity. One popular approach, increasingly being used in the United States and other countries, is built upon an industry model in which the network operator manages forward and spot electricity markets. Generators and buyers can submit bids to supply and purchase, respectively, electricity at specific locations or nodes on the network. The network operator then chooses the lowest-cost bids to balance electricity supply and demand subject to the physical laws that govern electric power networks and the capacity of the network to carry power reliably. The bid price of the last selected bidder (or the first higher bidder rejected) at a node becomes the market clearing price at that node. When the transmission network is congested, market-clearing prices will vary among locations or nodes. Prices are higher at locations that are import constrained and lower at locations that are export constrained. The differences between locational prices represent congestion charges that generators at low-priced locations pay to supply power to customers at high-priced locations.

Since both demand and transmission capacity availability vary over time, the incidence of network congestion, the differences in locational prices, and the congestion charges can also vary widely over time. The associated variations in prices create a demand by risk-averse buyers and sellers for instruments to hedge price fluctuations. In order to satisfy this demand, several ISOs in the United States, have created and allocated *financial transmission rights* (or FTRs) to market participants. These financial rights give their holders a claim on the congestion rents created when the network is constrained and allow them to effectively hedge variations in nodal price differences and associated congestion charges.

The above economic model can be described in its simplest and most general form, following Hogan (2003) by the following program:

$$\begin{aligned}
&\underset{d,g,y,u\in U}{Max} \quad B(d)-C(g)\\
&s.t.\\
&y=d-g\\
&L(y,u)+i^t y=0\\
&K(y,u)\leq 0
\end{aligned} \tag{2.3}$$

Here the vector $y=d-g$ is the net load at each location, *i.e.* the difference of demand and generation. The set in *U* consists of the various controls used by the system operator. The objective is the bid-based net benefit function, which is the difference between the bid benefit for demand $B(d)$ and the bid-cost for generation $C(g)$. The constraints balance actual losses *L* and net load $i^t y$. The (many) contingency limits define the security constraints in *K*, which are a complex function of transmission flows and other factors. The corresponding multipliers or shadow prices for the constraints *p, λ, η* stand for net loads, reference bus energy and transmission constraints, respectively. The FTRs are derived from these shadow prices.

Using the optimal solution (d^*, g^*, y^*, u^*) and the associated shadow prices, we obtain the vector of location prices, p^t, as:

$$p^t = \nabla B(d^*) = \nabla C(g^*) = \lambda i^t + \lambda \nabla L_y(y^*, u^*) + \eta^t \nabla K_y(y^*, u^*) \tag{2.4}$$

where L_y and K_y stand for $\frac{\partial L}{\partial y}$ and $\frac{\partial K}{\partial y}$, respectively.

Therefore, locational prices equal the marginal benefit of demand, which equals the marginal cost of generation, which in turn equals the reference price of energy plus the marginal cost of losses and congestion.

While the FTR approach provides an instrument to hedge against price fluctuation, FTRs alone cannot resolve the problem of incentives for long-term transmission expansion. In order for FTRs to do so the presence of a centralized ISO that allocates through an auction the necessary long term FTRs to protect the holders from future unexpected changes in congestion costs is necessary. Long term transmission rights work in parallel with long term generation contracts. The long term concept is important for expansion projects. Typically, the long term FTR allocation mechanism relies on the operation of a short-run spot market for energy and ancillary services by the ISO, and on a bid-based, security constrained, economic dispatch with nodal pricing. Authors in this area (Hogan, 2002b) see the long term FTR alternative as a merchant transmission investment because incremental FTRs can provide market-based transmission pricing that attracts transmission investment.

The definition of FTRs[9] is of crucial importance. As it has been reported earlier, FTRs result from the difference in locational prices, which, in a lossless network, is solely due to congestion. A FTR would pay the holder the spot price difference between nodes times a quantity specified in the contract. In other words a FTR with magnitude *t* from node *i* to node *j* would pay its owner $t(p_j - p_i)$. Since contract quantities do not depend upon actual flows, TCCs are not limited to nodes physically connected by a single link, and can be written on any pair of nodes in a network.

Bushnell and Stoft (1997) expands the concept of FTRs in order to obtain reduced transmission cost uncertainty; this is equivalent to providing a hedge against locational price differences for investors in power plants who would, in turn, sign long-term supply contracts with customers at other nodes. In that paper a form of a *contract for differences* (*CFD*) is suggested: a supplier at node *i*, who enters into a CFD with a consumer at node *j*, agrees to pay the consumer the difference between a negotiated strike price, P_c, and the true spot price, p_j, in exchange for a fixed payment. This financial contract is independent of the actual power injections and can therefore be negotiated without any supervision by the system operator. By arranging to receive p_j - p_c, if $p_j > p_c$ (or vice versa pay, if $p_j < p_c$), the customer now faces a constant price of p_c for the quantity specified in the CFD. If the spot prices at nodes *i* and *j* are always the same, the supplier is also guaranteed a price equal to p_c, since she will receive the spot price. The CFD, therefore, eliminates temporal price risks for the two parties of the contract. If, however, the spot prices of nodes *i* and *j* sometimes differ, the supplier is exposed to locational price risk. When the spot price for power is higher at the consumer's than at the

[9] In Bushnell and Stoft (1997) the FTRs are referred as *Transmission Congestion Contracts (TCCs)*. The difference between the two definitions are equivalent is that the second one is referred exclusively to a contract network regime. In this work, we keep the first more general expression, for illustrating purposes.

supplier's node and is above the strike price at the consumer's node, the supplier will suffer a marginal loss equal to the difference between the nodal prices. In such a case she cannot earn enough from her spot sales to compensate for her CFD obligations. Transmission congestion contracts were developed to eliminate this price risk. Through the combined application of a CFD and a matching FTR, Bushnell and Stoft (1997) argues that both the supplier and the consumer can eliminate price uncertainty.

A second approach to efficient allocation of congested network interfaces is to decentralize congestion pricing by creating and allocating another type of tradable transmission rights that give a holder *physical transmission rights* (or PTRs) to use congested transmission lines. Under this approach, the physical capacity of each of the potentially congested links is defined, and rights to use this capacity are created and allocated in some way to suppliers and consumers. A supplier must possess a physical right to have its produced electric power scheduled or ‘‘transported’’ over the congested interface. Once it has such a physical right, there is no additional charge for using the congested interface. The markets for these physical rights then determine the market-clearing prices for congestion. Note also that the holding of physical transmission rights also plays the same role as do financial rights in hedging variations in congestion prices, since rights holders pay no additional congestion charges. In this organization model, the ISO’s role is much more passive, relying primarily on bilateral contracting and private auction markets to determine which generators are dispatched at various times and how scarce transmission capacity is allocated.

The physical transmission rights, like FTRs, are also based upon the locational price difference. This means that PTRs pay each link owner the price difference between the nodes, served by that link, times the power flow on that link. Assuming no losses, this quantity is $q_{ij}(p_j - p_i)$, where q_{ij} is the power flow from i to j. Oren, et al. (1995) have called this form of revenue distribution *Link Based Rights* (LBRs). When a new line is constructed, its builder receives the rights to revenue from flows on that line. This approach has been used in Chile and Argentina. Owners of transmission lines therefore earn revenues proportional to the power flows on their lines.

Despite the similarities between physical and financial rights, there are also some important differences between these two concepts. First, the PTRs refer to actual power flow between two nodes. This means that, unlike FTRs, they can only be applied (or written) between nodes that are physically connected by a single link. Second, while both financial and physical transmission rights can enhance electricity seller or buyer market power in essentially the same ways, the physical rights may potentially have worse welfare properties than financial rights, since they can be withheld from the market, reducing effective transmission capacity and inducing production inefficiency. The superiority of FTRs over physical rights has been analytically demonstrated in the literature. As a result the physical rights approach is not used widely in practice. To this concurs also the fact that tracing physical flow through a transmission network meets many practical difficulties.

2.2.3. Discussion over Transmission Network Investments

From the previous discussion it becomes obvious that whether based on financial or physical transmission rights, the merchant transmission investment model encounters many difficulties and has, for this reason, received substantial criticism. As Hogan (2003) argues, the most important problems-possibly unsolvable-for merchant investment stem from economies of scale and scope.

If transmission investments could always be made in small increments relative to the size of the market as a whole, they would have a minimal effect on market prices. In such a case, acquisition of the financial transmission rights could provide the proper incentive, since prices would not differ significantly before and after the network expansion, despite the increase in capacity. The FTRs would provide the hedge against transmission prices, and the arbitrage opportunity in the spot market would be sufficient for the investor to justify the investment. By contrast, in the presence of economies of scale, *lumpy investment* in transmission expansion may both expand transmission capacity while having an ambiguous effect on market prices. Hence, while the investment may be economically justified because the savings in total operating costs exceed than the investment cost, the resulting value of the FTRs at the new locational prices may not be able to cover that cost. Moreover, with significant returns to scale, prices may change substantially not only at the nodes involved in the investment, everywhere else: since everyone may wait for somebody else to make the investment, the latter might never take place.

Bushnell and Stoft (1996) brings further doubts on the efficiency of the market driven incentives for network modifications by pointing out a serious problem related to the incentives they provide for investment in the grid. The problem that a nodal spot-pricing market structure has to face is the danger of under-investment in the grid expansion or even no investment at all. This problem is created by the fact that efficient nodal prices contain network congestion and loss elements. If transmission owners collect revenues based upon these prices, they may have an incentive to increase, rather than reduce, congestion and losses. As an extreme case, there is the possibility for an investor to build a line intentionally congested, hence profitable even though the net social surplus of the system decreases due to artificially created congestion.

In the same vein Joskow and Tirole (2005) distinguishes transmission network investments in two categories: network deepening investments and network expansion investments. The former category involves physical upgrades of the facilities on the incumbent's existing network, *e.g.* adding capacitor banks, phase shifters, reconstructuring existing transmission links *etc*. These investments are physically intertwined with the incumbents' facilities. Similar to network deepening investments are network maintenance decisions. On the other hand network expansion investments involve the construction of separate new links (including parallel links) that are not physically intertwined with the incumbent network, except at connection points at either end. These investments can, at least in principle, be made either by incumbent transmission owners, stakeholders (generators, load-serving entities), or a third-party merchant investor. Joskow and Tirole (2005) shows that a merchant model is unlikely to be applied successfully to network deepening investments, because this mechanism requires free entry to the development of new transmission investments. It is unlikely for the entrants to have information about the existing transmission lines similar to that of the incumbents, and they will be discouraged or even avoid to entry to the market. Therefore, entry is likely to be blockaded, which implies that network deepening investments can only be undertaken by the existing transmission network owners.

In the same article, it is also underlined that the difficulties the merchant model run through result from the fact that the model ignores too many important attributes of transmission networks and the behavior of transmission owners and system operators. By dealing directly with issues associated with lumpy investment, market power in wholesale power markets, gaming behavior of merchant investors and stochastic attributes of transmission capacity, the Transco model appears to be superior to an ISO because it avoids separation between transmission ownership and system operations. However, the regulated Transco will necessarily confront inefficiencies resulting from asymmetric information and political interference in the planning and investment processes. It may also be less effective than a merchant model in providing the incentives for the introduction of innovative transmission investment options, construction costs minimization and efficient tradeoffs between generation and transmission investments.

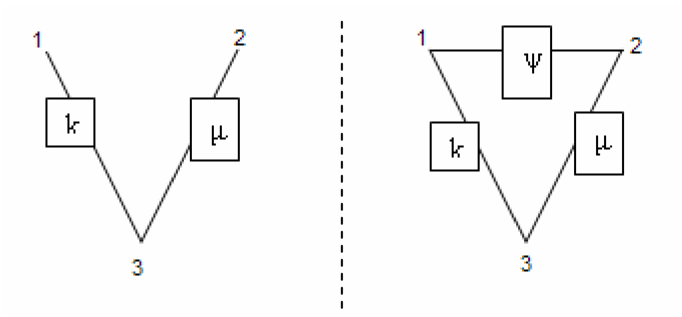
As a result, Hogan (2003) proposes a concept that draws a line between merchant and regulated investments. That work states that anything that is lumpy and makes a big impact on the market would be difficult to be undertaken by the merchant model, due to the fact that FTRs awarded to the investors may not guarantee the transmission investment cost recovery. It is, therefore, suggested that a combination between merchant and regulated transmission investment should be the core of the organization of electricity markets. Under this regime, regulated transmission investment would be limited to cases where the investment is inherently large and lumpy relative to the size of the relevant market. Further, “large” would be defined as large enough to have such an impact on market prices that the ex post value of FTRs and other explicit transmission products could not justify the investment. In any other case the investments should be left to the market.

In conclusion, most researchers converge to the idea that it is unlikely for policymakers to solely or even primarily rely on a merchant model to govern transmission investment. The limited amount of merchant investment that has been undertaken to date in electricity markets where it has been allowed is consistent with this view. An important research challenge is to develop good regulatory mechanisms to apply to regulated Transcos which also provide opportunities for merchant investors to develop projects when merchant investments appear to be the most efficient options.

Chapter 3: The model

The aim of this work is to examine how a lumpy network expansion may affect the entire electric power system. We focus our analysis on the impact of an addition of a new transmission line on the total social surplus and generators' welfare, and try to determine whether it is possible for an investment to have negative effects on welfare due to its negative externalities created on other market participants.

We use the following simple topology of an electric power system with 3 nodes.



a) **b)**

Figure 3. 1

We suppose that the initial system has the form of the figure 3.1(a). The electric power system consists of three regions (Area 1, 2, 3), which are connected with two transmission lines. The maximum of electric power that can be transferred through each line is determined by its capacity. The capacities of each line are illustrated in figure 3.1. Let *K*, *M* represent lines $1 \to 3$ and line $2 \to 3$, respectively, with *k*, *μ* representing their respective capacity[10]. We assume that areas at nodes 1 and 2 are the generation regions and at the node 3 there is the electric power consumer (*i.e.* a city). The two generators (1, 2) are competing with each other in the city located in point 3.

[10] Unless otherwise indicated in this work lines are represented by upper-case letters, while their capacities by lower-case ones.

We suppose that a new investment takes place, such that line *Ψ* with capacity *ψ* is added to the existing network giving the network the form it has on figure 3.1(b). The main reason of this modification of the transmission grid lies on the need of obtaining a reservation line. Such an expansion provides a new connection path for the electric power flow, therefore, when a line collapses, there still is an alternative connection path among the three nodes of the system. Consider for instance the case where the line *K* collapses[11]. While under normal operation consumers at point 3 were supplied by both generators, in the absence of line *Ψ*, generator 1 can not provide electric power to the consumer when line *K* collapses. With line *Ψ*, the failure of line *K* does not isolate generator 1 from the node 3. Thus, the presence of line *Ψ* supports a more adequate supply for consumers.

Despite its importance in the case of adversity, line *Ψ* may cause negative externalities in the regular operation of the system, since its addition changes dramatically the topology of the system and imposes new constraints in the power flow. In the analysis below, we examine the system under emergency and normal operation focusing on the impact of the new line on the total social surplus and the generators' profits, in order to determine both under what conditions such a lumpy investment is socially optimal to undertake, as well as when it is also privately profitable.

For simplicity we make also the following assumptions:

a) Assumption 1: The inverse demand function is linear and its form is the following: $P = a - bQ$, where Q is the sum of the outputs of the two generator ($Q = q_1 + q_2$).

b) Assumption 2: In order to simplify the implications of Kirchoff's laws, we assume the three lines of the network are identical, this means that, except for transmission capacities, all the other parameters of the grid are the same[12].

c) Assumption 3: The two electric power firms sell electricity at node 3 competing with each other in quantities (*Cournot competition*).

d) Assumption 4: The monopoly output of generator 2 is less than the capacity *μ* of line *M*.

[11] A transmission line may collapse for various reasons such as weather extremities, line overloading *etc*.

[12] In technical terms, the lines have the same length and resistance.

e) *Assumption 5:* The capacity μ is binding for the power flows from node 2 to node 3, when the whole electric power produced flows through line *M* and both generators try to produce their duopoly output.

f) *Assumption 6:* The two firms have constant marginal costs, c_1 and c_2 respectively. We also assume that generator 2's marginal cost is bigger or at least the same with generator 1's cost, $c_1 \leq c_2$.

Before continuing the analysis, let's consider how capacity constraints limits, imposed by Kirchoff's laws, are modified due to the assumptions made. According to Kirchoff's laws, the flows of the interconnected system of Fig. 1(b) must satisfy the following conditions:

$$\begin{aligned} q_{1\to 3} &= \frac{2q_1^{\psi}}{3} + \frac{q_2^{\psi}}{3} \\ q_{2\to 3} &= \frac{2q_1^{\psi}}{3} + \frac{q_1^{\psi}}{3} \\ q_{1\to 2} &= \frac{q_1^{\psi}}{3} - \frac{q_2^{\psi}}{3}, \quad if\ q_1^{\psi} > q_2^{\psi} \end{aligned} \tag{3.1}$$

where q_i (i=1,2) is the electric power produced by the generator i and the superscript ψ refers to the case that line Ψ has been added to the grid. As long as lines are capacity constrained, the above flows must not exceed the corresponding capacities, which implies:

$$q_{1\to 3} \leq k \Rightarrow \frac{2q_1^{\psi}}{3} + \frac{q_2^{\psi}}{3} \leq k \tag{3.2a}$$

$$q_{2\to 3} \leq \mu \Rightarrow \frac{2q_1^{\psi}}{3} + \frac{q_1^{\psi}}{3} \leq \mu \tag{3.2b}$$

$$q_{1\to 2} \leq \psi \Rightarrow \frac{q_1^{\psi}}{3} - \frac{q_2^{\psi}}{3} \leq \psi \tag{3.2c}$$

Since we have assumed that the monopoly output of generator 2 is less than the capacity μ (assumption 4), the second inequality above is always binding, yielding

$$q_{2\to3} = \frac{2q_2^{\psi}}{3} + \frac{q_1^{\psi}}{3} = \mu \Leftrightarrow 2q_2^{\psi} + q_1^{\psi} = 3\mu \tag{3.3}$$

In what follows we examine electric power flows under regular and emergency conditions, with and without line *Ψ.* In all the cases, the profit maximization problem will be subject to the corresponding constraints.

3.1 Regular Operation of the electric network

3.1.1. Without line Ψ

Consider first the case where the system operates under regular conditions and line *Ψ* has not been constructed. According to Cournot competition each firm attempts to maximize its profits, subject to capacity constraints in (2) and taking the other firm's output as given. The maximization problem for firm 1 has the following form:

$$\begin{aligned} &Max \;\; \Pi_1 = q_1 P - c_1 q_1 \\ &s.t. \;\; q_1 \le k \end{aligned} \tag{3.4a}$$

Respectively, firm 2 tries to maximize its profits which are given by the expression below:

$$\begin{aligned} &Max \;\; \Pi_2 = q_2 P - c_2 q_2 \\ &s.t. \;\; q_2 \le \mu \end{aligned} \tag{3.4b}$$

Solving the two maximization profit problems, we derive the following Cournot outputs:

$$\begin{aligned} q_1^{c} &= \frac{a - 2c_1 + c_2}{3b} \\ q_2^{c} &= \frac{a - 2c_2 + c_1}{3b} \end{aligned} \tag{3.5}$$

where the exponent *c* refers to Cournot output, and a, b are the parameters of the inverse demand function. Then the total output consumed in region 3, where consumers are located, is:

$$Q^c = q_1{}^c + q_2{}^c = \frac{a - c_1 - c_2}{3b} \tag{3.6}$$

Social welfare is defined as the sum of consumer surplus plus generators' profits, *i.e.* ,

$$\begin{aligned} S^{no\Psi} &= \Pi_1^c + \Pi_2^c + CS^{no\Psi} \\ CS^{no\Psi} &= \frac{b(q_1^2 + q_2^2)}{2} \end{aligned} \tag{3.7}$$

where $S^{no\Psi}$ is social welfare without line *Ψ* and $CS^{no\Psi}$ is the corresponding consumer surplus and Π_i^c refers to the Cournot profits of generator *i*. From (6) we also have that

$$P = a - bQ^c = \frac{2a + c_1 + c_2}{3} \tag{3.8}$$

Moreover, the generators' surplus defined by the sum of their profits becomes in the Cournot equilibrium:

$$\begin{aligned} \Pi_{1,\mathrm{TOT}}^c &= \Pi_1^c + \Pi_2^c \Rightarrow \\ \Pi_{1,\mathrm{TOT}}^c &= \frac{2a^2 + 5c_1^2 - 8c_1c_2 + 5c_2^2 - 2a(c_1 + c_2)}{9b} \end{aligned} \tag{3.9}$$

The shaded area on Fig. 3.2 depicts social surplus under the assumption that firm 1 is more efficient ($c_1 < c_2$). The dark and light grey areas represent social surplus created by firm 1 and firm 2, respectively. The triangle $\tilde{P}A\bar{P}$ represents total consumer surplus.

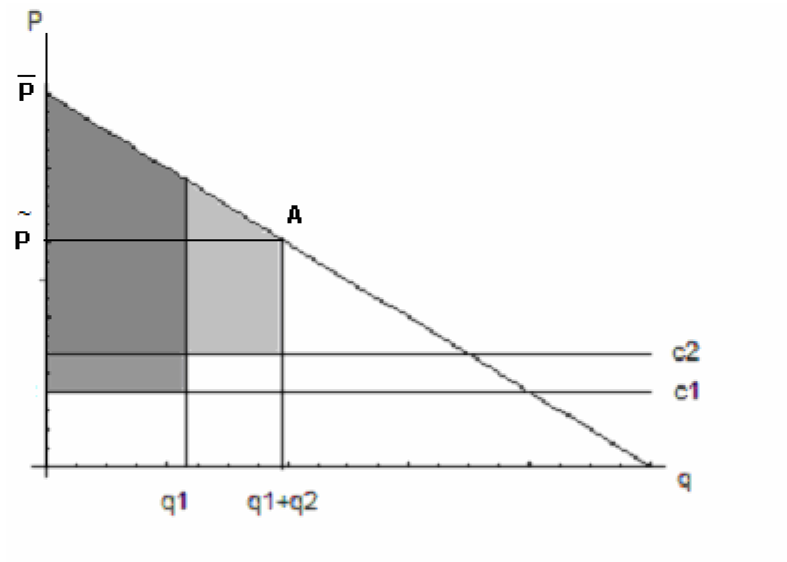


Figure 3. 2

Substituting equilibrium values of profits and consumer surplus from (9) and (7), respectively, into the social surplus definition, we get, after a few manipulations:

$$S_1^{no\Psi} = \frac{2a^2 + 5c_1^2 - 8c_1c_2 + 5c_2^2 - 2a(c_1 + c_2)}{6b} \tag{3.10}$$

3.1.2. In presence of line Ψ

Let us now examine social welfare and generators' profits when a network expansion such as that described in Fig. 3.1(b) takes place. The new line not only changes the topology of the entire network, but also imposes a more complex system of constraints. The maximization problem the firms are facing now becomes:

$$\begin{aligned} &Max \;\; \Pi_i = q_i P - c_i q_i \\ &s.t. \;\;\; 2q_1 + q_2 \le 3k \\ &\qquad\;\; 2q_2 + q_1 = 3\mu \end{aligned} \tag{3.11}$$

Since μ, the capacity of line *M*, is not able to transmit the duopoly output of both electricity companies (assumption 5), we assume that there is a predetermined rule, which determines each firm's share over the congested line. Outputs q_1^{ψ} and q_2^{ψ} are determined as

$$\begin{aligned} q_1^{\psi} &= 3r\mu \\ q_2^{\psi} &= \frac{3}{2}(1-r)\mu \end{aligned} \qquad (3.12)$$

where r defines generator 1's right on line *M*, and $1-r$ is the corresponding right of generator 2. Firm 1's right *r* is taken as an exogenous variable that $r \in (0,1)$. When $r = 1$, generator 1 produces its monopoly output while generator 2 produces nothing; the opposite occurs when $r = 0$. Due to Kirchoff's laws, the distribution of rights on *M* affects total output, Q^{ψ}, transmitted in the consumer region (node 3) since it also affects the amount of power transferred through line *K*:

$$Q^{\psi} = q_1^{\psi} + q_2^{\psi} = \frac{3}{2}(1+r)\mu \quad > \mu \, . \qquad (3.13)$$

Since $\mu \in [0,1]$ it is evident from (13) that $Q^{\psi} = [\frac{3}{2}\mu, 3\mu]$ and also that $\frac{dQ^{\psi}}{dr} > 0$. The total generators' profit and the social surplus are given by the below equations, respectively

$$\Pi_{1,\mathrm{TOT}}^{\psi} = -\frac{3}{4}\mu(-2c2(-1+r) + 4c1r - 2a(1+r) + 3b\mu + 6br\mu + 3br^2\mu) \qquad (3.14)$$

$$S_1^{\psi} = \frac{3}{8}\mu(4c_2(-1+r) - 8c_1 r + 4a(1+r) - 3b\mu - 18br\mu + 9br^2\mu \qquad (3.15)$$

3.1.3. The value of line ψ in welfare terms, when system operates normally

Having estimated welfare and profits under both the presence and absence of line *Ψ*, we are now in measure to evaluate the social and private value of this line. In our analysis the cost of constructing the line will be ignored unless otherwise mentioned. This allows us to concentrate on the impact of line *Ψ* on the rest of the network. It must, however, be kept in mind that constructing lines of very high capacity - as to never be constrained - may be very costly.

In estimating welfare both in the presence and absence of line *Ψ* under normal operation of the network, it becomes obvious that it is possible for a network expansion, like this, to hurt the social welfare and/ or the generators profits, even if its construction cost is zero. In what follows we examine under what conditions such a scenario may hold.

Since total welfare depends on total output of the electric power industry transmitted to the consumer region, it can be shown that:

Proposition 2: *The presence of line Ψ may reduce total output produced and, hence, total social welfare. More specifically if capacity μ is quite small then* $Q^{\Psi} < Q^{c}$.

Proof: Let us consider the case that the total output with line *Ψ* is smaller than output without line *Ψ* ($Q^{\Psi} < Q^{c}$). Solving the above inequality and also using equations (3.6) and (3.13) we get that

$$Q^{\psi} < Q^{c} \Leftrightarrow \mu < \frac{2(2a - c1 - c2)}{9b(1+r)} \tag{3.16}$$

The above inequality determines an upper bound for the capacity of line *M*, beneath which the new line is harmful for social welfare. If the capacity *μ* is less than $\mu_a = \frac{2(2a - c1 - c2)}{9b(1+r)}$ then the line *Ψ* hurts the social surplus. In the opposite situation when $\mu > \mu_\alpha$, the network expansion is optimal for the social surplus. ♦

From the expression of μ_α (3.16), it becomes that μ_α varies inversely to *r.* When *r* increases (generator 1 is allowed to transmit more), the value μ_α decreases, and the case where $Q^{\psi} < Q^{c}$ becomes less likely, reducing, thus, the risk for Ψ to be detrimental. This is due to the fact that the low cost generator (generator 1) supplies more electricity to the generation node.

In order to examine whether producers win or lose when the network is being expanded, we estimate the change of profits caused by the modification of the electric grid. The change in generators' surplus is expressed in the following equation:

$$\begin{aligned}
&\Delta\Pi_{1,\mathrm{TOT}} = \Pi^{\psi}_{1,\mathrm{TOT}} - \Pi^{c}_{1,\mathrm{TOT}} \Leftrightarrow \\
&\Delta\Pi_{1,\mathrm{TOT}} = \frac{1}{36b}(-4(2a^2 + 5c_1^2 - 8c_1c_2 + 5c_2^2 - 2a(c_1 + c_2)) + \\
&54b(a - c_2 + (a - 2c_1 + c_2)r)\mu - 81b^2(1+r)^2\mu^2)
\end{aligned} \tag{3.17}$$

Proposition 3: *There exist two values of* μ, $\mu_2 < \mu_1$*, (specified on equations (3.18) and (3.19) below) such that* $\Pi^{\psi}_{1,\mathrm{TOT}} < \Pi^{c}_{1,\mathrm{TOT}} \ \forall \ \mu \notin (\mu_2, \mu_1)$*, or vice versa when* $\mu \in (\mu_2, \mu_1)$.

Proof: It becomes clear that whether producers win or lose from the new line depends on the sign of the expression (3.17). The change in producers' profits is a function of capacity μ and the exogenous parameter of rights, r, considering all other parameters as constant. Setting $\Delta\Pi_{1,\mathrm{TOT}} = 0$ yields the following roots:

$$\begin{aligned}
&\mu_1 = \frac{1}{9b^2(1+r)^2}(3ab(1+r) + 3b(c_2(-1+r) - 2c_1r) + \\
&\sqrt{(b^2(-4(2a^2 + 5c_1^2 - 8c_1c_2 + 5c_2^2 - 2a(c_1 + c_2))(1+r)^2 + 9(a - c_2 + (a - 2c_1 + c_2)r^2)))}
\end{aligned} \tag{3.18}$$

$$\begin{aligned}
&\mu_2 = \frac{1}{9b^2(1+r)^2}(3ab(1+r) + 3b(c_2(-1+r) - 2c_1r) - \\
&\sqrt{(b^2(-4(2a^2 + 5c_1^2 - 8c_1c_2 + 5c_2^2 - 2a(c_1 + c_2))(1+r)^2 + 9(a - c_2 + (a - 2c_1 + c_2)r^2)))}
\end{aligned} \tag{3.19}$$

The roots μ_1 and μ_2 are functions of the parameter r and define an interval within which the change in producers' surplus is positive. Otherwise, if μ does not belong to this interval, generators will lose after the construction of line Ψ. In other words

$$\begin{aligned} &if \quad \mu \in (\mu_2, \mu_1) \quad then \quad \Delta\Pi_{1,\mathrm{TOT}} > 0 \\ &if \quad \mu \notin (\mu_2, \mu_1) \quad then \quad \Delta\Pi_{1,\mathrm{TOT}} < 0 \end{aligned} \tag{3.20}$$

given that $\mu_1 > \mu_2$. ♦

Hence, line *Ψ* reduces profits in two cases:

- when *μ* is very small and the presence of *Ψ* reduces an already suboptimal output.
- when *μ* is sufficient large. Now the presence of *Ψ* allows both duopolists to increase their output in a situation where joint profit maximization requires an output restriction.

We turn now our attention on the impact of line *Ψ* on the profits of producer 1 (low cost generator). As already shown, before the network investment, generator 1 produces $q_1^c = \dfrac{a - 2c_1 + c_2}{3b}$ and its profits are $\Pi_1^c = \dfrac{(a - 2c_1 + c_2)^2}{9b}$. When line *Ψ* is constructed, the generator 1's output and profits become respectively

$$q_1^{\psi} = 3r\mu \tag{3.21}$$

and $$\Pi_1^{\psi} = -\frac{3}{2} r\mu(-2a + 2c_1 + 3b(1+r)\mu) \tag{3.22}$$

The change in the low cost producer's profits created by the network expansion is therefore:

$$\begin{aligned} &\Delta\Pi_1 = \Pi_1^{\psi} - \Pi_1^c \Leftrightarrow \\ &\Delta\Pi_1 = -\frac{(a - 2c_1 + c_2)^2}{9b} + 3(a - c_1) r\mu - \frac{9}{2} br(1+r)\mu^2 \end{aligned} \tag{3.23}$$

Proposition 4: *There exist two values of* μ *,* $\mu_3 < \mu_4$ *, such that firm 1's profits decrease when* $\mu \in (\mu_3, \mu_4)$*, otherwise if* $\mu \notin (\mu_3, \mu_4)$ *then the line* Ψ *has a positive impact on the profits of generator 1.*

Proof: The proposition is proven using the same methodology as before and finding the values of capacity μ that nullify the expression (3.23).

$$\mu_3 = \frac{1}{9b^2(r+r)^2}(3abr - 3bc_1r - \frac{1}{18}\sqrt{(-648b^2(a-2c_1+c_2)^2 r(1+r) + (54abr - 54bc_1r)^2)}) \quad (3.24)$$

$$\mu_4 = \frac{1}{9b^2(r+r)^2}(3abr - 3bc_1r + \frac{1}{18}\sqrt{(-648b^2(a-2c_1+c_2)^2 r(1+r) + (54abr - 54bc_1r)^2)}) \quad (3.25)$$

These values define a new interval (μ_3, μ_4) for the capacity of line *M* in which

$$\begin{array}{llll} if & \mu \in (\mu_3, \mu_4) & then & \Delta\Pi_1 > 0 \\ if & \mu \notin (\mu_3, \mu_4) & then & \Delta\Pi_1 < 0 \end{array} \quad (3.26)$$

This means that whether producer 1 wins or loses from the addition of line *Ψ* depends on the capacity *μ*, since *μ* determines his transportation ability, and, thus, his output level.♦

The expressions in (3.26) show the importance of capacity *μ* on the change in firm 1's profits, $\Delta\Pi_1$. As illustrated above, it has different effects in the change of social welfare and producers' profits. In order to find out these different impacts we must determine how these intervals of *μ* tangle with each other. For this purpose we proceed numerically. Taking into account that generator 1 is the low cost producer ($c_1<c_2$) we will also assume that the expression $\alpha + c_1 - 2c_2$ will always be positive, in order to rule out trivial cases[13].

Due to the complexity of the problem we use the following example. Let $a = 10, b = 1, c_1 = 2, c_2 = 3$[14]. Under these assumptions we draw Fig. 3.3 which

[13] When $\alpha + c_1 - 2c_2 < 0$, *μ's* are not real numbers. Moreover, if this inequality is valid, the high cost producer does not produce in equilibrium

[14] We have performed our simulations for many sets of initial parameter values. The results presented below are qualitative quite robust in changes in parameters. Some non-important

depicts the evolution of μ_α, μ_1, μ_2, μ_3, μ_4 as function of r. We remind that r takes prices between 0 and 1.

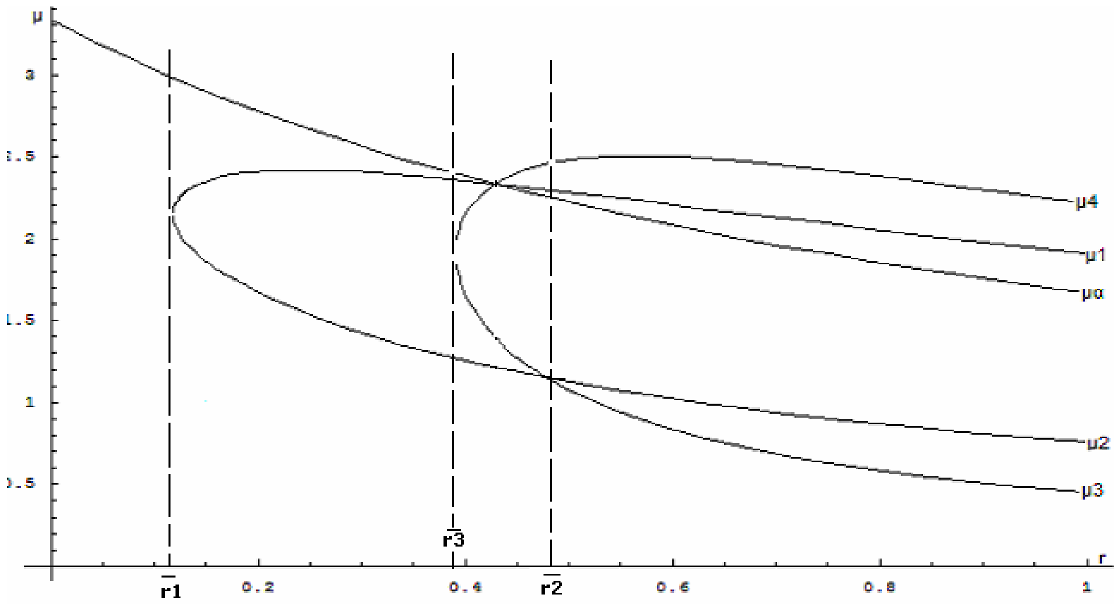


Figure 3.3

From Fig. 3.3 it is clear that for the values of r in which all *μ's* are real numbers the classification of the intervals is possible and standard to be made. For $r < \bar{r}_3$, the critical values of μ, μ_3, μ_4 are not real numbers, hence, the expression of $\Delta\Pi_1$ is always negative, meaning that generator 1 always loses from the new line addition. This is explained by the fact that when r is small enough, generator 1 obtains a little share of the market; therefore, she has little interest in investing in the network. Moreover, when $r < \bar{r}_1$, the change in total profits is always negative for the same reason as above.[15]

changes that may occur under different initial parameter values are discussed in the appendix.

[15] The values of $\bar{r}_1, \bar{r}_2, \bar{r}_3$ depend on the initial parameter values. When these values change, the results for the $\bar{r}_1, \bar{r}_2, \bar{r}_3$ differ from those shown in Fig. 3.3. See Appendix A.

Assuming $r > \bar{r}_2$ the relation among the critical values of μ when the system operates normally is summarized in the following figure:[16]

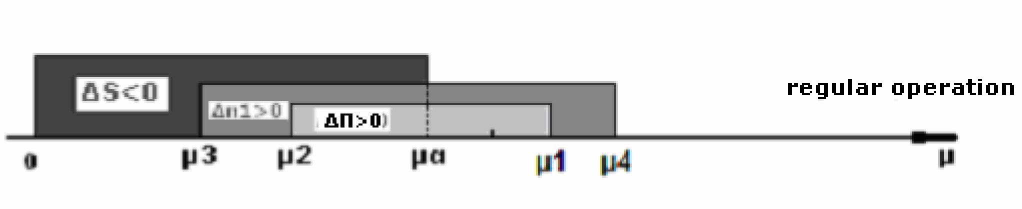


Figure 3. 4

The most interesting result illustrated in the above graph, is when $\mu \in (\mu_3, \mu_2)$. In this case the network expansion hurts social surplus, the change in the total producers' profits is negative, yet generator 1 still has incentives to invest in the construction of line *Ψ*. In other words, generator 1 has bigger interest for investment in line *Ψ* than its competitor, since this expansion gives her the possibility to continue supplying the consumption area. This statement is proven by the fact that the interval (μ_3, μ_4) is larger than the interval (μ_2, μ_1). From Fig. 3.4 we can once again conclude to the fact that the new line investment may be harmful to social surplus,[17] due to the negative externalities it creates. More specifically, line *Ψ* may decrease the social welfare when capacity *μ* is very small, since it makes the transmission constraints even tighter.

The following table illustrates the impact of adding line *Ψ* to the network on social surplus, change in total profits and generator's 1 profits under all the different combinations of *μ's*:

Capacity μ	ΔS	$\Delta\Pi_{1,TOT}$	$\Delta\Pi_1$
$\mu \in (0, \mu_3)$	-	-	-
$\mu \in (\mu_3, \mu_2)$	-	-	+
$\mu \in (\mu_2, \mu_a)$	-	+	+
$\mu \in (\mu_a, \mu_1)$	+	+	+
$\mu \in (\mu_1, \mu_4)$	+	-	+

[16] Fig. 3.4 has been traced for $r > \bar{r}_2$.

[17] When $\mu \in (0, \mu_a)$

$\mu > \mu_4$	+	-	-

Table 1

If generators have identical production costs $(c_1 = c_2)$,[18] the results of the above analysis slightly change. In the case that the system works normally the results are shown in Fig. 3.5.

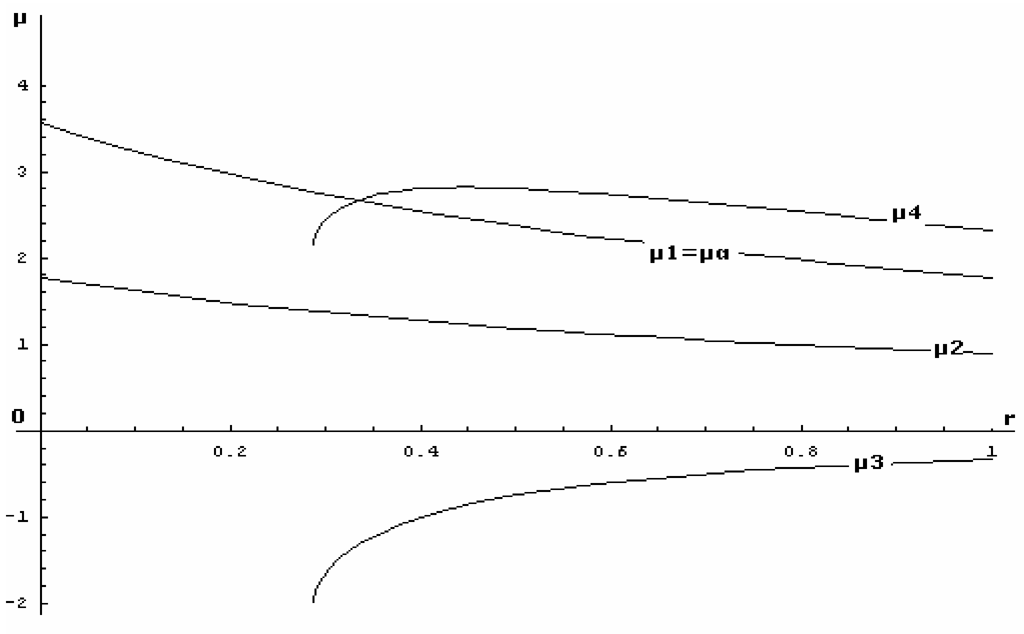


Figure 3. 5

In Fig. 3.5 we keep the same notation with that of Fig.3.4. It becomes obvious that the classification of the critical *μ's* does remain the same. The difference between the two cases is limited to the values that some critical *μ's* get, i.e. the capacity μ_α that determines the upper bound that $\Delta S < 0$ is equal to μ_1, and since μ_3 takes negative values for all $r's$, the latter is excluded from the analysis. However, the results derived from the analysis, when the costs are different, are generally the same with those, when the two firms have the same costs. The second ones are illustrated in Table 2.

Capacity μ	ΔS	$\Delta\Pi_{TOT}$	$\Delta\Pi_1$
$\mu \in (0, \mu_2)$	-	+	+

[18] The case of the identical cost generators is analytically represented in the Appendix B. In this part of the thesis only the results are illustrated.

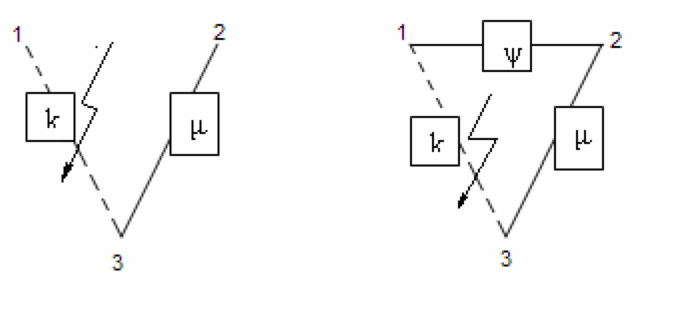
$\mu \in (\mu_2, \mu_1)$	-	+	+
$\mu \in (\mu_1, \mu_4)$	+	-	+
$\mu > \mu_4$	+	-	-

Table 2

3.2. Emergency operation of the electric system

In this part of the project we focus on the impact of line *Ψ* when a part of the network collapses due to adverse circumstances, like extreme weather conditions (storms, frost etc.) or technical problems (line overloading). The construction of line *Ψ* is mainly imposed by technical reasons, in order to maintain the electric power system stability at high levels, in emergency conditions. An outage of an important line that transfers energy to large consumers, may lead to the collapse of the entire electric power system, causing obvious problems in the supply of consumers. Except for the need of having a reservation line in the system, line *Ψ* can also contribute in the more economic dispatch of electricity. More specifically, considering Fig.3.5, if $c_1 < c_2$, the new line guarantees that the cheaper energy of node 1 will be transmitted to the consumers, no matter if line *K* collapses or not. Thus, besides guaranteeing an adequate level of electricity supply at node 3, line Ψ allows also for cheaper provision since, at least, part of the total energy consumed at node 3 originates from the cheaper producer.

Suppose, now, that following an adversity line *K* collapses. The network, with and without the presence of line *Ψ*, is shown in the figure below.



a) b)

Figure 3. 6

Below, we proceed with the analysis of the impact of line *Ψ* in emergency situations, following the same steps as in section 3.1.1, 3.1.2, 3.1.3.

3.2.1. Without line Ψ

At the beginning consider that line *Ψ* is not part of the network. In this case producer 1 loses its ability to produce, since it has no other connection path with the consumer region, than the broken line *K*. On the other hand, generator 2 is being better off, because it can produce at its monopoly level. The output of the two generators is, therefore:

$$\begin{aligned} q_1 &= 0 \\ q_2 &= q_2^M = \frac{a-c_2}{2b} \end{aligned} \tag{3.27}$$

As a result the electric power that is transmitted to the consumers is $Q_2^{no\psi} = q_1^{no\psi} + q_2^{no\psi} = \frac{a-c2}{2b}$ and the profits of the firm 2 are $\Pi_2 = \frac{(\alpha - c2)^2}{4b}$.
Recall that from assumption 4, the monopoly output of generator 2 is less than capacity *μ*, therefore, part of the capacity of line *M* will remain unutilized.
In this situation the social surplus is given below

$$S_2^{no\Psi} = \frac{3(a-c_2)^2}{8b} \tag{3.28}$$

3.2.2. In presence of line Ψ

Assume now that the reservation line has been constructed. In a crisis (line *K* collapses) generator 1 remains in the system, since line *Ψ* provides a new connection path between the generation node 1 and the load area. We assume again that the two producers make use of their rights on line *μ*, therefore, total output as well as individual outputs are

$$q_1^{\psi} = r\mu$$
$$q_2^{\psi} = (1-r)\mu \qquad (3.29)$$
$$Q^{\psi} = q_1^{\psi} + q_2^{\psi} = \mu$$

The equations that describe outputs in this case differ from those contained in expression (3.12) in part 3.1.2; the difference stemming from differences in the constraints that are binding. When line *K* collapses, electric power flows only through line *M*, whose capacity consists an upper bound to the quantity consumed at node 3. Unless μ is very large, total output will always equal to μ. Under these circumstances, the profits of each firm are illustrated below:

$$\Pi_1^{\psi} = r\mu(\alpha - c_1 - b\mu) \qquad (3.30)$$

$$\Pi_2^{\psi} = (-1+r)\mu(-\alpha + c_2 + b\mu) \qquad (3.31)$$

Moreover, the total profits of electricity industry and the social surplus are now:

$$\Pi_{2,\text{TOT}}^{\psi} = -\mu(-a + c_2 + b\mu + c_1 r - c_2 r) \qquad (3.32)$$

$$S = \frac{1}{2}\mu(2a - b\mu + 2c_2(-1+r) - 2c_1 r - 2b\mu r + 2b\mu r^2) \qquad (3.33)$$

3.2.3. The value of line Ψ when line K collapses

In this part we estimate the change in social welfare and generators' profits created by the construction of line *Ψ*, in the case of an outage in line *K*, thereby determining the value of line *Ψ* from a social and private point of view. For this purpose we use the same methodology as in section 3.1.3.

Without the investment in line *Ψ*, the electric power (Q_2) produced is equal to the monopoly output of generator 2 in the emergency operation of the network. The construction of line *Ψ*, however, creates an alternative path for the power flow from node 1 to node 3, so, when line *K* collapses the total output of the electricity industry (both generator 1 and generator 2) is equal to the capacity of line *M*. Hence:

$$Q_2^{no\psi} = q_1^{\ no\psi} + q_2^{\ no\psi} = q_2^M = \frac{a - c_2}{2b} \tag{3.34}$$

$$Q^{\psi} = q_1^{\psi} + q_2^{\psi} = r\mu + (1 - r)\mu = \mu \tag{3.35}$$

Taking into account that the monopoly output of generator 2 is less than the capacity of line *M* (assumption 4*)*, we conclude that

$$Q^{no\psi} < Q^{\psi} \tag{3.36}$$

This means that in an emergency operation of the system, total output is larger in the presence of line *Ψ*. In welfare terms, this implies that line *Ψ* improves social surplus in a crisis by increasing the total output of the electric industry. Consumers become, also, better off by the presence of line *Ψ*, while, the change in the producers' surplus is still ambiguous.

More specifically, the change in firm 1's profit is obviously positive, since in the absence of *Ψ*, he produces nothing and when *Ψ* is constructed, he produces q_1^{ψ} *kWs*. Accordingly, firm 2 becomes certainly worse off, since in the absence of *Ψ* she produces at her monopoly output, while with line Ψ she produces $q_2^{\psi} < q_2^M$. The question that remains is what happens with the total producers' surplus, since firm 1's profits increase, and vice versa for firm 2's ones. Therefore, the change in total producers' surplus, $\Delta\Pi'_{\mathrm{TOT}}$, is defined as below

$$\Delta\Pi'_{\mathrm{TOT}} = \Pi_1^{\Psi} + \Pi_2^{\Psi} - \cancel{\Pi_1^{no\Psi}} - \Pi_2^{no\Psi} \tag{3.37}$$

where Π_i^{Ψ} and $\Pi_i^{no\Psi}$ are the profits when line *Ψ* exists are the profits when line *Ψ* does not exist in the transmission system, respectively. Calculating the above equation we get

$$\Delta\Pi'_{\mathrm{TOT}} = (c_2 - c_1)r\mu - \frac{(-a + c_2 + 2b\mu)^2}{4b} \tag{3.38}$$

The line *Ψ* may have positive or negative effects on total profits of electricity industry, depending on the value of capacity *μ*. To determine these impacts we introduce the following proposition:

Proposition 5: *There exist two values of* μ, $\mu' < \mu''$, *such that* $\Delta\Pi'_{\mathrm{TOT}} > 0,\ \forall\ \mu \in (\mu', \mu'')$, *and vice versa when* $\mu \notin (\mu', \mu'')$.

Proof: In order to find out the effect of the line *Ψ* on the producers' surplus, we must estimate the sign of the expression (3.38). The roots of the above equation are

$$\mu' = \frac{1}{2b^2}\left[b(a + c_2(-1+r) - c_1 r) - \sqrt{b^2(c_1 - c_2)r(-2a - c_2(-2+r) + c_1 r)}\right] \quad (3.39)$$

$$\mu'' = \frac{1}{2b^2}\left[b(a + c_2(-1+r) - c_1 r) + \sqrt{b^2(c_1 - c_2)r(-2a - c_2(-2+r) + c_1 r)}\right] \quad (3.40)$$

Thus,

$$\begin{aligned} &if \quad \mu \in (\mu', \mu'') \quad \Delta\Pi'_{\mathrm{TOT}} > 0 \Rightarrow \sum \Pi_i^{\Psi} > \sum \Pi_i^{no\Psi} \\ &if \quad \mu \notin (\mu', \mu'') \quad \Delta\Pi'_{\mathrm{TOT}} < 0 \Rightarrow \sum \Pi_i^{\Psi} < \sum \Pi_i^{no\Psi} \end{aligned} \quad (3.41)$$

The above results determine the intervals of *μ* in which line *Ψ* improves the producers' surplus in the case of problematic network operation. If capacity *μ* does not belong to this interval, when line *K* collapses, total profits of generators decrease in the absence of line *Ψ*.♦

Using the same numeric values of parameters *a, b,* c_1 and c_2, as in section 3.1.3 we draw the following diagram, which depicts the evolution of *μ΄, μ΄΄* for $\forall r \in [0,1]$. In the same figure we add also the expressions of μ_α, μ_1, μ_2, μ_3, μ_4, as functions of *r* ,for illustrating purposes.

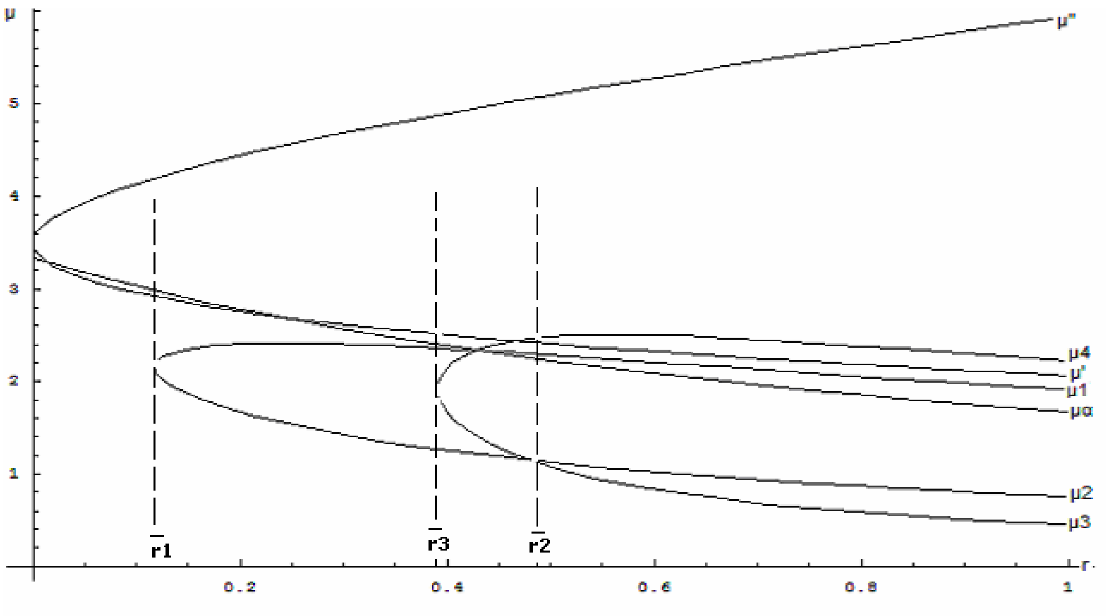


Figure 3. 7

Fig. 3.6 illustrates the classification of the critical values of *μ*. The sign of the total social surplus and the producers' surplus in the two conditions of network (regular and emergency operation) depends on the intervall that capacity *μ* belongs to. All possible situations are shown in the conclusive graph below, for a given value of *r*, that is bigger than $\bar{r}_2$ $(r > \bar{r}_2)$[19].

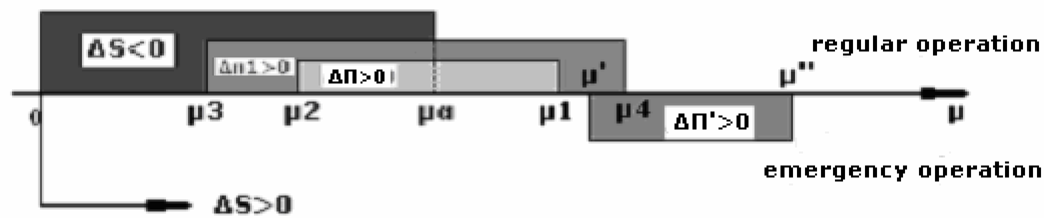


Figure 3. 8

Consider, now, that the two firms have the same production costs $(c_1 = c_2)$. When line *K* collapses the impact of line *Ψ* on social welfare, as it has been already pointed out, depends on the change of the total output. The change in total output is:

$$\Delta Q = \mu - \frac{a - c_2}{2b} \tag{3.42}$$

[19] For the determination of $\bar{r}_1, \bar{r}_2, \bar{r}_3$, see section 3.1.3.

Recalling our fourth assumption[20], the addition of line *Ψ* in the network has always positive impact on the social welfare, when line *K* collapses, since the above expression is a positive value ($\Delta Q > 0$). Taking into account the change in the total profits of generators and using the same methodology as before, we conclude that generators are always being worse off, when there is an outage in line *K*. The explanation of this result is quite simple: when line *Ψ* is not part of the network, the only producer is the firm 2 in the emergency case and it produces its monopoly output. When line *Ψ* is added, the two identical firms compete with each other a la Cournot (symmetric Cournot). In this case the total output of the generators may be at most equal to the monopoly output of generator 2. If the total output is equal to the monopoly output of firm 2, there is no change in the profits of electricity industry. In all the other cases the electricity industry is being worse off, since the total output is less than the monopoly output produced when there is no network modification.[21]

[20] *I.e.* that the monopoly output of generator 2 is less than the capacity *μ.*

[21] The case of the identical cost generators is analytically represented in the Appendix B.

Chapter 4: Incentives for efficient investments in the electric network

So far we have proven that there is a possibility for a detrimental network investment to take place. However such an investment hurts the social welfare and may have negative effects to the generators' profits, as well. So, it is important to develop a model that excludes 'bad' modifications of the network. Such a model has been produced by *Bushnell and Stoft* in their paper 'Electric Grid Investment under a Contract Network Regime' in 1996. In the following text we will firstly represent their model and then we will expand it in the way that only efficient investments may occur in the electric network.

4.1. Incentives to avoid detrimental network investments

The issue of investment incentives within a contract network regime has first been addressed by Hogan in "Contract Networks for Electric Power Transmission" (1992). In this work, market participants are allowed to purchase and trade FTRs, which pay the owner the locational price difference between the two nodes specified in the contract.

Bushnell and Stoft (1996) addresses these investment incentive issues in the context of a contract network regime. That paper presents an allocation rule based upon the concept of awarding the new property rights created by investments to market participants. This requires making a formal correspondence between the set of all FTRs and the network dispatch, *i.e.* the electric power that can be transferred through the network. This is possible because each FTR is defined by a power flow between two nodes. By adding together (consolidating) the power flows associated with all allocated FTRs, we find a set of injections and demands at the various nodes in the network corresponding to some particular dispatch. Under the concept of feasible allocation, an investor in the grid is allowed to select any set of FTRs which, when combined with the existing set, corresponds to a dispatch which is feasible under the constraints of the newly modified grid. An expander who creates an intentionally congested line which effectively reduces the feasible set of dispatches would, therefore, be required to accept a set of FTRs that exactly cancel the flows that are no longer feasible in the resulting, lower capacity network. The concept of feasibility provides, therefore, some check on the incentive to create congestion.

Bushnell and Stoft's analysis assumes a network consisting of N nodes indexed by i, j = 1… N and K market participants indexed by k =1 … K. Associated with the nodes are power injections q_i and spot prices p_i. Supply to the grid is indicated by a positive injection, while consumption from the grid is indicated by $q_i < 0$. Often we will be interested in a complete set of q_i or p_i for $1 < i < N$, which we will represent with the vectors q and p, respectively. Since agents may buy and sell power at more than one node, injection vectors are useful for describing agents, and we denote the injections of agent k by q^k. The sum of all agents' injection vectors is called the system dispatch, thus $q = \sum_k q^k$ is the system dispatch.

An *optimal dispatch, q*,* maximizes social surplus, which is calculated as the difference between consumption benefits and production costs. We represent both costs and benefits by a cost function $C(q)$ that takes negative values in the case of benefits from use. Each agent has a cost function $C^k(q^k)$, which is convex by assumption. The social surplus, which results from a dispatch q, is defined as

$$\begin{aligned} &W(q) = \max - \sum_k C^k(q^k) \\ &s.t. \quad \sum_k q^k = q \end{aligned} , \tag{4.1}$$

Associated with the optimal dispatch is an *optimal price vector p*,* which induces the optimal dispatch, q^*.

To facilitate the analysis, a FTR of size t from node i to node j is denoted by t_{ij}. To simplify notation when summing sets of FTRs, we choose instead to define a FTR of quantity z from i to j as an N-vector, where the *ith* and *jth* elements are the only non-zero elements. Thus $t = (0, -\tau, 0, ..., 0, \tau, 0)$ where $t_i = -\tau$ and $t_j = \tau$, is such a FTR. The combination of all FTRs owned by agent k can be expressed as the vector sum $t^k = \sum_{t \in T^k} t$, where T^k is the set of all FTRs owned by agent k. Since *p*t* gives the revenue from a single TCC, $p*t^k$ gives the total revenue from an agent's set of TCCs.

Now, if we don't take into account the *contracts for differences (CFDs)*[22], which someway or other cancel each other out when CFDs are consolidated over the entire market, the net benefit of an agent is

$$NB^k(p,t^k) = p*q^k + p*t^k - C^k(q^k) \tag{4.2}$$

The change in net benefit of the group holding net contract position t, both before and after the price changes from *p* to *p',* caused by the network investment, is $\Delta NB(t) = NB(p',t) - NB(p,t)$. Only contracts in position t are considered when computing the net benefits even if new ones acquired during the interval.

So far we have discussed the consolidation of FTRs for groups of agents, which are accomplished simply by summing the contract vectors of individual agents. A special case of this, which is needed for the definition of a feasible allocation, is the group of all participating agents. We denote the complete set of allocated FTRs by *T*, and consolidate them into a single vector by summing all agents' FTR vectors: $T = \sum_k t^k$. Since *p* t* gives the revenue from a single FTR, *p*T* gives the revenue from the set of all allocated FTRs. Now, we can define *NB(p,T)* to be the aggregate net benefit of all the agents in the market.

$$NB(p,T) = \sum_k NB^k(p,t^k) = p*T + p*q - \sum_k C^k(q^k) \tag{4.3}$$

We will show that when the current set of allocated contracts, corresponding to some feasible dispatch, matches the current dispatch of the system, the property rights generated by a detrimental modification to the grid will be of negative value. This result is driven by the ability of FTRs to insulate market participants from the negative effects of price fluctuations. As detrimental modifications of the grid are defined the ones that decrease the social surplus under optimal dispatch. In other words they are those that cause the following result in the welfare:

[22] Recall that the CFD concept has analytically been presented at section 2.2.2.

$$\Delta W = W(q') - W(q) < 0 \tag{4.4}$$

If the consolidated set of all transmission contracts, *T*, matches optimal dispatch *q*, then the new set of contracts, $\tilde{T}$, allocated under the feasibility rule to the maker of a detrimental modification (ΔW < 0) will have a negative value that is at least as large in magnitude as the loss in social surplus: $p^{'} * \tilde{T} < \Delta W$, where *p′* is the optimal price vector after modification and *q′* is optimal for *p′*.

Before proceeding to the above proof is quite important to underline that when all transmission contracts, *T*, match the dispatch, *i.e.* the allocation rule is valid, then the aggregate net benefit of the market participants is equal to the social welfare. Actually, from equations (4.1) and (4.2) it becomes clear that when $T = -q$ then

$$NB(p,T) = -\sum_k C^k(q^k) = W(q) \tag{4.5}$$

Considering the aggregate net benefits before and after the network modification, respectively, we obtain the following

$$NB(p,T) = W(q) \tag{4.6}$$

$$NB(p',T+\tilde{T}) = NB(p',T) + p'\tilde{T} \le W(q') \tag{4.7}$$

The inequality (4.7) arises because the total rights, after the modification of the network, do not match the dispatch of the system, ($T + \tilde{T} \neq q$). Subtracting "before" from "after" we have

$$\begin{gathered} \Delta NB(T) + p'\tilde{T} \le \Delta W \Rightarrow \\ p'\tilde{T} \le \Delta W - \Delta NB(T) \end{gathered} \tag{4.8}$$

The change in net benefits*)* is always positive, $\Delta NB(T) \ge 0$, for any price change, given the convexity of *C(q)*. The equation (4.8) shows that the revenue from any set of contracts selected by the detrimental investment

($\Delta W < 0$) under the feasibility allocation rule will have negative value. From this result, an important conclusion about the incentives for grid investment immediately follows.

If the consolidated set of all transmission contracts matches the current dispatch, then an outside party, with no prior interest in the grid, will not invest in a detrimental alteration of the grid.

In other words, the Bushnell and Stoft's mechanism provides some protection against bad modifications under the assumption that the rights which have been allocated match the current dispatch of the system. Note that while Bushnell and Stoft's (B&S) mechanism is effective in providing right incentives to new entrants, the possibility that an agent, who has already invested in the network, may find it profitable to modify the grid in a detrimental way still remains. Such an incentive would exist when the agent's gains from current transmission contracts and spot market injections outweigh the revenues from the new transmission contracts, which must be negative.

4.2. Incentives for efficient network investments

While B&S mechanism protects the electric system from "bad" investments in the network, it does not guarantee that all "good" investments will pass the test: together with "bad" investments, some efficient ones may also be excluded. If transmission contracts, *T*, match optimal dispatch ($T = -q*$), then equation (4.8) implies that there are no incentives for an investor to proceed to detrimental modifications of the network. However, it also implies that there may be efficient modifications that still are non-profitable for the investors. This is the case when $\Delta W \geq 0$ (efficient investment), but also $\Delta W - \Delta NB(T) \leq 0$. Under these circumstances, the acquired revenue from the new rights will be negative, $p' * \widetilde{T} \leq 0$. This means that such an investment will not be done, and by this way some efficient ones will be excluded.

In what follows, we extend the above model in the opposite direction. In the next section, we propose a mechanism to provide incentives for efficient investments in the electric grid. Two conditions are examined, that a) there is certainty in the demand and supply, and b) that supply and demand are characterized by uncertainty.

4.2.1. There is certainty over demand and supply

In order to organize efficiently the electricity market under the contract network regime proposed in the Bushnell and Stoft's paper, we have to find a mechanism that not only precludes detrimental investments but also gives motivation for efficient investments. For this purpose, we introduce into the model a subsidy to the new transmission investors. The answer to the question of how investments will be subsidized within a deregulated electricity sector, is that the subsidy must be provided by the electricity market itself. Thus, the necessary money for this subsidy must be obtained from the agents already in the network, in the form of a lump-sum tax. We assume that the subsidy for the efficient investments equals the change in the aggregate net benefits created by the network modification. That is,

$$S = \Delta NB(T) \tag{4.9}$$

Taking the maximum values of the revenues acquired by the new rights, the expression (4.8) becomes

$$p' * \tilde{T} = \Delta W - \Delta NB(T) + S \tag{4.10}$$

On the other hand we assume that the tax, τ^k, imposed on each agent is equal to the change in her net benefit caused by the grid investment, $\tau^{\mathrm{k}} = \Delta NB(t^k)$. Now, we must prove that it is feasible to subsidize the new network investments taking this amount from the incumbents in the form of lump-sum tax. Taking first the expression of the subsidy and using the expression (4.3), we have

$$\begin{aligned} &S = \Delta NB(T) = NB(p',T) - NB(p,T) \Rightarrow \\ &S = p' * q - p' * q + p' * T - p * T - \sum \left[C^k(q^k(p')) - C^k(q^k(p)) \right] \end{aligned} \tag{4.11}$$

Also, for the lump-sum tax in each agent we have that

$$\begin{aligned} &\tau^k = \Delta NB(t^k) = p' * q - p * q + p' * T - p * T - \left[C^k(q^k(p')) - C^k(q^k(p)) \right] = \\ &(p' - p) * q^k + (p' - p) * t^k - \left[C^k(q^k(p')) - C^k(q^k(p)) \right] \end{aligned} \tag{4.12}$$

Aggregating (4.12) yields

$$\begin{aligned} &\sum \tau^k = \sum \Delta NB(t^k) = \\ &(p' - p) * \sum q^k + (p' - p) * \sum t^k - \sum \left[C^k(q^k(p')) - C^k(q^k(p)) \right] \end{aligned} \tag{4.13}$$

Having that $\sum q^k = q$ and $\sum t^k = T$, and combining the equations (4.11) and (4.12) we conclude to the expression below:

$$S = \sum t^k \tag{4.14}$$

This means that the total lump-sum tax payment from all agents provides adequate revenues in order to subsidize efficient investments. By this mechanism the revenue an investor obtains from a network investment equals to the change in social welfare, since the subsidy, *S*, equals by assumption the change in net benefits, *ΔNB(T)*, so:

$$p' * \tilde{T} = \Delta W \tag{4.15}$$

The last result leads to two very important conclusions about the motivations provided to potential investors:

1. If $\Delta W \leq 0$ (the case of a detrimental investment), the revenue from the rights created by the new investments, $p' * T \leq 0$, will be negative. In other words, this mechanism does not provide incentives for bad investments.

2. If $\Delta W \geq 0$ (the case of an efficient investment) then the revenue from new rights will be always positive, $p' * T \geq 0$, and the investors will have the motivation to invest efficiently in the network.

4.2.2. There is uncertainty over demand and supply

So far we have focused on the case that demand and supply have been considered to be known with certainty. Nevertheless, the electricity market is characterized by large scale uncertainty, it is, therefore, important to examine whether the above mechanism provides incentives for efficient network modifications in an uncertain environment as well. This will bring our results much closer to real world situations. According to Ghali, Gonzalez and Roland, the equation (4.8) becomes *under uncertainty*

$$\mathrm{E}_s\left(p_s' * \tilde{T}\right) = \mathrm{E}_s \Delta W - \mathrm{E}_s \Delta NB(T) \tag{4.16}$$

where $\mathrm{E_s}$ denotes expectations. Using the same model as before, we have again a subsidy $S = \mathrm{E}_s \Delta \Pi(T)$ and a lump-sum tax in each existing agent $\tau^k = E_s \Delta NB(t^k)$. By subsidizing the new investments, the expected revenues gained from a network investment become

$$\mathrm{E}_s\left(p_s' * T\right) = \mathrm{E}_s \Delta W - \mathrm{E}_s \Delta NB(T) + S \tag{4.17}$$

We have to prove again the revenue adequacy that makes such a subsidy feasible. In other words, we must prove that $S = \sum \tau^k$. Analyzing the expression of subsidy first, we conclude to the following:

$$\begin{aligned} &S = \mathrm{E}_s \Delta \Pi(T) = \Delta \mathrm{E}_s(\Pi(T)) = \mathrm{E}_s \Pi(p_s', T) - \mathrm{E}_s \Pi(p_s, T) = \\ &\mathrm{E}_s\left[p_s' * Q_s\left(p_s'\right) + p_s' * T - C(Q_s(p_s'))\right] - \mathrm{E}_s\left[p_s * Q_s(p_s) + p_s * T - C(Q_s(p_S))\right] \Leftrightarrow \\ &S = \mathrm{E}_s\left[p_s' * Q_s(p_s') - p_s * Q_s(p_s)\right] + \mathrm{E}_s\left[(p_s' - p_s) * T\right] - \mathrm{E}_s\left[C(Q_s(p_s')) - C(Q_s(p_s))\right] \end{aligned} \tag{4.18}$$

Also, we have that

$$\begin{aligned}
&\sum t^k = \sum \mathrm{E}_s \Delta\Pi(t^k) = \\
&\sum \Big[\mathrm{E}_s \left[p'_s * Q^k(p'_s) - p_s * Q^s(p_s) \right] + \mathrm{E}_s((p'_s - p_s) * t^k) - \mathrm{E}_s \left[C^k(Q^k_s(p'_s)) - C^k(Q^k_s(p_s)) \right] \Big] = \\
&\mathrm{E}_s \left[p'_s * \sum Q^k(p'_s) - p_s * \sum Q^k(p_s) \right] + \mathrm{E}_s((p'_s - p_s) * \sum t^k) - \mathrm{E}_s \left[\sum C^k(Q^k_s(p'_s)) - \sum C^k(Q^k_s(p_s)) \right]
\end{aligned} \tag{4.19}$$

From the last two equations and taking also into account that

$$\begin{aligned}
&T = \sum t^k \\
&\sum Q^k(p) = Q_s(p) \quad and \\
&\sum C^k(Q^k_s(p)) = C(Q_s(p))
\end{aligned} \tag{4.20}$$

we can straightforwardly conclude the desirable adequacy. It follows that, on average, the collected revenue from lump-sum tax imposed on incumbent network participants will be sufficient to cover the necessary subsidies for the efficient investments. Hence, the conclusions of the section 4.2.1 can be generalized easily in a stochastic environment.

In conclusion, if the subsidy equals the change in net benefits created by the grid alteration, then the total revenues from new rights are equal to the change in the social welfare (whether there is certainty or uncertainty). Thus, the investors' incentives become compatible with the social welfare: Investors lose when social welfare decreases and win when they invest on efficient modifications of the electric network. In this way the mechanism proposed in the last section not only excludes detrimental investments, as does the one proposed in B&S (1996), but also provides the necessary incentives for the agents to invest on the network in an efficient way.

Chapter 5: Conclusions

This work has, at its first section, presented the most important points of the literature related to the reconstruction of the electricity sector and the models developed in order to apply it in practice. We are about to conclude that either under the merchant transmission investment option or under the regulatory regime the difficulty to provide adequate investment incentives still remains. Thus, we tend to the opinion, also quite extended in the literature, that drawing a line between merchant investments and regulated ones seems to be the most sufficient way to the reorganization of electricity markets. Thus, the lumpy investments would be undertaken by the regulated Transco, while merchant investors would be allowed and also motivated to develop projects in smaller scale, where the latter are the most efficient options.

We have developed a simple model aiming to capture an important feature of electricity markets, namely, the negative externalities created by a lumpy network investment due to the loop flow problem implications. We have shown that adding a new line in the existing network is not a rather complex matter. Despite its contribution in adequate energy supply and satisfaction of the reservation needs of the system, the new line can affect social surplus and generators' profits in a detrimental way. Our analysis has proven that a new line, even with sufficient large capacity, can have negative results both under emergency and normal network operation. These "bad" effects actually rise from the fact that the new line tightens the capacity constraints of the existing network links according to the implications of Kirchoff's laws. Therefore, it is quite intuitive that a new line investment may not have the desirable consequences, unless it is followed by an adequate capacity increase of other lines of the network. In such a case the possibility the new line hurting social surplus would be eliminated.

Furthermore, it becomes clear from our analysis that generators may have conflicting interests in a new line investment. In the model presented generator 1 is strongly interested in the investment, since she always earns more in an emergency situation. On the other hand generator 2 must oppose the investment, since her output decreases after the line is constructed. The opposite scenario occurs when some other part of the network collapses.

Therefore, we can straightforwardly come to the conclusion that in a merchant investment regime the investment will be undertaken by the firm, whose line has the biggest possibility to fall out. However, with identical collapse possibilities the problem of under-investment still remains.

At the last section of this work we have developed a mechanism that guarantees there will be no possibility for efficient investment to be excluded. Considering the Bushnell and Stoft model, we propose a new mechanism that is based on subsidizing the agents in order to invest in the network expansion. We have proven that there can be revenue adequacy for this subsidy by imposing a lump-sum tax on the agents already existed in the electricity markets. Therefore, this mechanism, not only prevents detrimental investments to take place, but also provides incentives to the agents to develop socially optimal projects. We have also shown this conclusion to hold in both stochastic and non-stochastic environments.

Appendix A

In this part we perform our simulations made in section 3.1.3 for different set of the initial parameters a,b,c_1,c_2. The results, which are illustrated in the figures below, provide a complete intuition of how the intervals of *μ* change when the parameters of the problem are diversified. In the following graphs, we also illustrate the changes in the values of the constants $\bar{r}_1,\bar{r}_2,\bar{r}_3$.

From the diagrams below we can straightforwardly conclude that different sets of the initial parameter values do not create significant differences in the results of the analysis made in section 3.1.3, since the do not modify the classifications of the intervals. Therefore, our former discussion can easily be extended $\forall a,b,c_1,c_2$ that satisfy the inequality: $\alpha + c_1 - 2c_2 > 0$[23]. However, some trivial remarks can be made. Notice, for instance, that as a becomes greater, the critical values μ_1 and μ_α converge to each other, and the interval (μ_3,μ_4), which determines the bounds where $\Delta\Pi_1 > 0$ is extended to all $r \in [0,1]$.

- For $a = 10, c_1 = 5, c_2 = 6, b = 1$

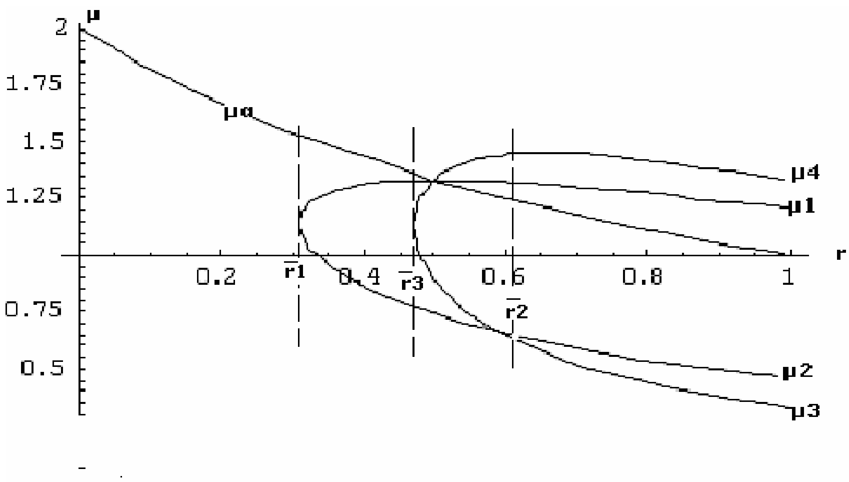


Figure A. 1

[23] See at section 3.1.3.

- For $a = 10, c_1 = 2, c_2 = 3, b = 2$

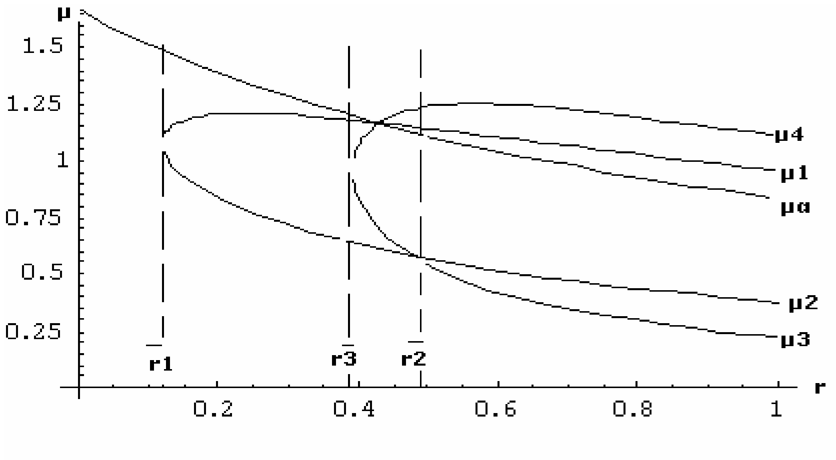


Figure A. 2

- For $a = 5,\ c_1 = 2,\ c_2 = 3,\ b = 1$

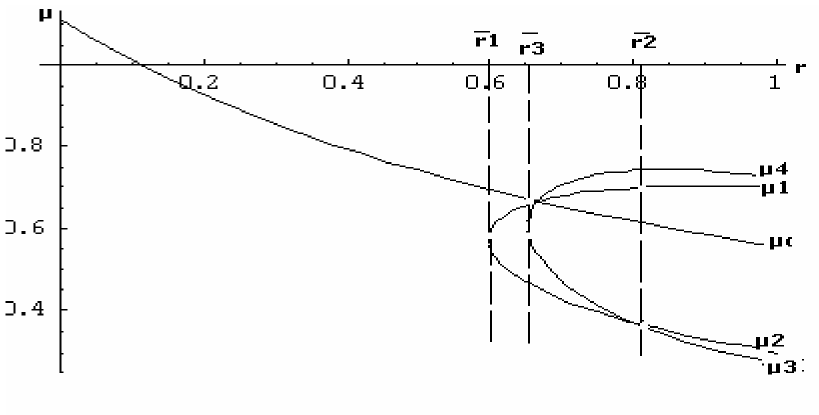


Figure A. 3

- For $a = 15,\ c_1 = 2,\ c_2 = 3,\ b = 1$

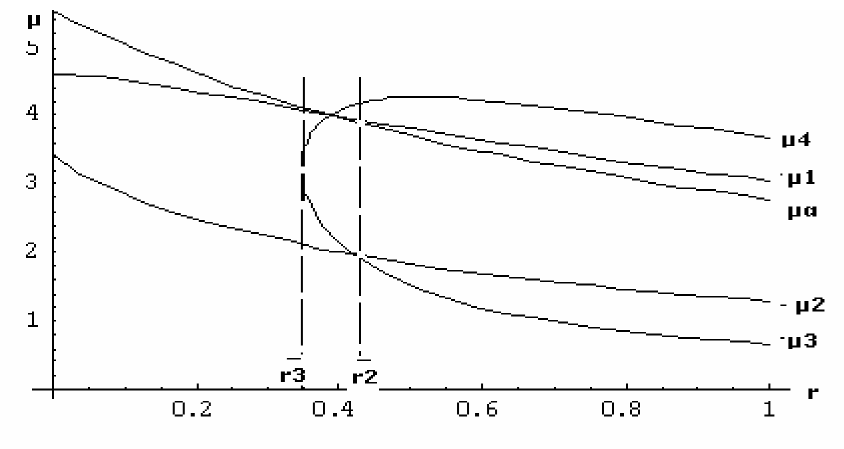


Figure A. 4

- For $a = 50,\ c_1 = 2,\ c_2 = 3,\ b = 1$

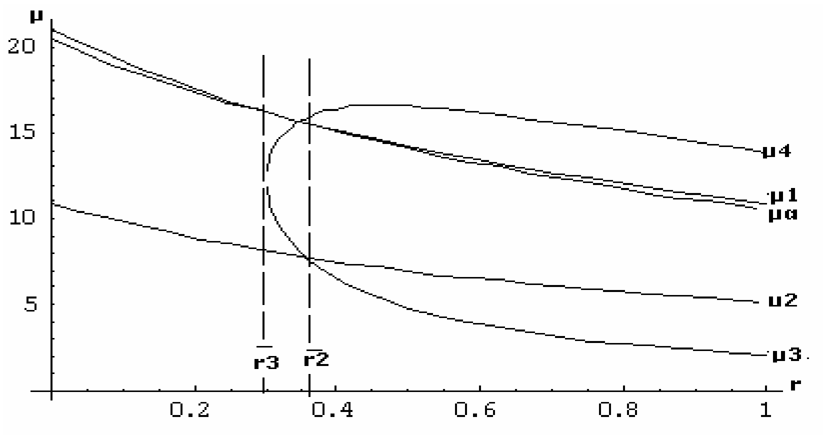


Figure A. 5

Appendix B

Consider that the two firms are symmetric having identical marginal costs, $c_1 = c_2 = c$. Under regular conditions we have a symmetric Cournot competition and substituting the equality of costs into the expressions 3.16, 3.18, and 3.19 and following the analysis in Chapter 3 we conclude that:

Proposition A.1: *The presence of line Ψ may reduce total output produced and, hence, total social welfare. More specifically if capacity μ is quite small then* $Q^{\Psi} < Q^{c}$.

The above statement is valid when $\mu < \mu_\alpha$ and since $c_1 = c_2$ the former inequality becomes:

$$\mu < \mu_\alpha = \frac{4(a-c)}{9b(1+r)} \tag{A2.1}$$

Proposition A.2: *There exist two values of* μ, $\mu_2 < \mu_1$, *such that* $\Pi^{\psi}_{1,\mathrm{TOT}} < \Pi^{c}_{1,\mathrm{TOT}}\ \forall\ \mu \notin (\mu_2, \mu_1)$, *or vice versa when* $\mu \in (\mu_2, \mu_1)$.

In this case the critical values μ_1, μ_2 are expressed below

$$\mu_1 = \frac{4(\alpha-c)}{9b(1+r)} \tag{A2.2}$$

$$\mu_2 = \frac{2(\alpha-c)}{9b(1+r)} \tag{A2.3}$$

Proposition A.3: *There exist two values of* μ, $\mu_3 < \mu_4$, *such that firm 1's profits decrease when* $\mu \in (\mu_3, \mu_4)$, *otherwise if* $\mu \notin (\mu_3, \mu_4)$ *then the line* Ψ *has a positive impact on the profits of generator 1.*

Substituting into the equations 3.24 and 3.25 we get

$$\mu_3 = \frac{-3abr + 3bcr + b(a-c)\sqrt{r(-2+7r)}}{9b^2(r+r^2)} \tag{A2.4}$$

$$\mu_4 = \frac{3abr - 3bcr + b(a-c)\sqrt{r(-2+7r)}}{9b^2(r+r^2)} \tag{A2.5}$$

If we represent the above results into a diagram we obtain the graph illustrated on Fig. 3.5.

Under emergency network conditions the results obtained from the section 3.2.3 are diversified. Estimating the change in total profits under the assumption that two firms have equal costs we derive the following:

$$\Delta\Pi^{'}_{\mathrm{TOT}} = -\frac{(-a+c+2b\mu)^2}{4b} \tag{A2.6}$$

From equation A2.6 we easily conclude that in the emergency network operation the change in total profits is always negative. In other words, the addition of line *Ψ* has always negative impact on the total profits of electricity industry, except for the case where $\mu' = \frac{a-c}{2b}$[24]. In this case the change in the profits is equal to zero meaning that firms are indifferent about the investment on line *Ψ*. All possible situations under normal and emergency conditions of the network are illustrated in the conclusive graph below:

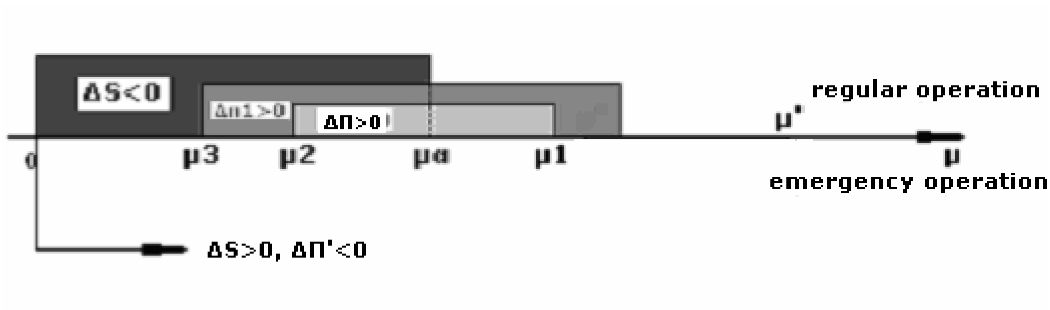


Figure B. 1

[24] Recall that the monopoly output of the firms is $q^M = \frac{a-c}{2b}$

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